



Promoting Safe, Secure, and Peaceful Growth of Nuclear Energy: Next Steps for Russia and the United States

Citation

Project on Managing the Atom and Russian Research Center "Kurchatov Institute". 2010. Promoting Safe, Secure, and Peaceful Growth of Nuclear Energy: Next Steps for Russia and the United States. Cambridge, Mass.: Report for Belfer Center for Science and International Affairs, Harvard Kennedy School, October 2010.

Published Version

http://belfercenter.ksg.harvard.edu/publication/20476/promoting_safe_secure_and_peaceful_growth_of_nuclear_energy.html

Permanent link

<http://nrs.harvard.edu/urn-3:HUL.InstRepos:27537560>

Terms of Use

This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at <http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA>

Share Your Story

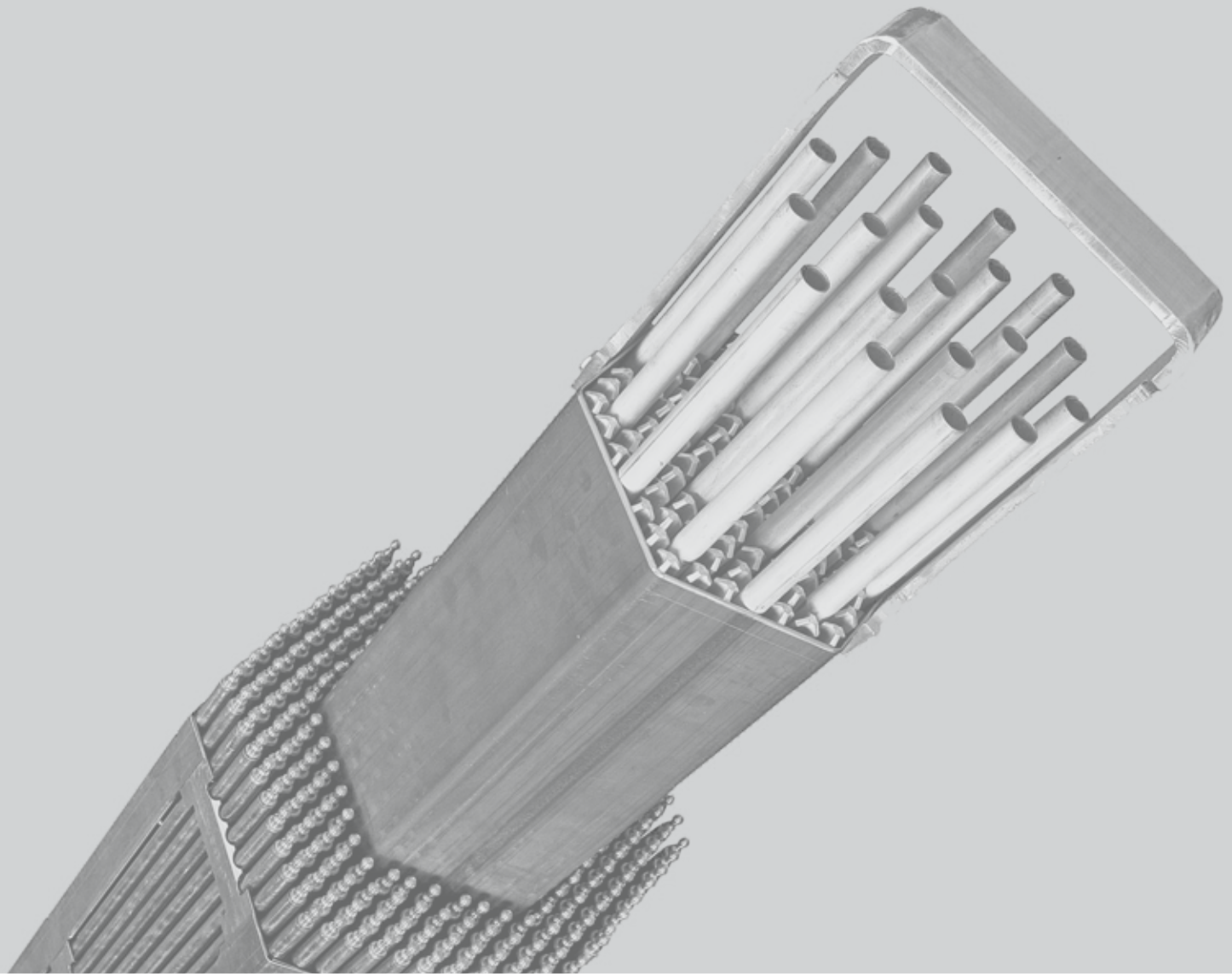
The Harvard community has made this article openly available.
Please share how this access benefits you. [Submit a story](#).

[Accessibility](#)

PROJECT ON MANAGING THE ATOM &
RUSSIAN RESEARCH CENTER “KURCHATOV INSTITUTE”

PROMOTING SAFE, SECURE, AND PEACEFUL
GROWTH OF NUCLEAR ENERGY:

NEXT STEPS FOR RUSSIA AND THE UNITED STATES



HARVARD Kennedy School
BELFER CENTER
for Science and International Affairs



Russian Research Center
KURCHATOV INSTITUTE

OCTOBER 2010

Belfer Center for Science and International Affairs

Harvard Kennedy School
79 JFK Street
Cambridge, MA 02138
Fax: (617) 495-8963
Email: belfer_center@harvard.edu
Website: <http://belfercenter.org>

Russian Research Center “Kurchatov Institute”

1, Academician Kurchatov Sq.
123182 Moscow, Russia
Fax: +7 499 196 18 70
E-mail: mvk@kia.ru
Website: www.kia.ru

Project Directors:

Matthew Bunn
Vyachevslav P. Kuznetsov

Participants:***Harvard University:***

Graham T. Allison
Martin B. Malin
Steven E. Miller
Andrew Newman
William H. Tobey

Kurchatov Institute:

Andrei Yu. Gagarinski
Nikolai N. Ponomarev-Stepnoi
Vladimir M. Schmelev
Stanislav A. Subbotin
Victor F. Tsibulski
Evgeniy P. Velikhov

Acknowledgments

This project was supported by a generous gift from an anonymous donor, with additional funding from the John D. and Catherine T. MacArthur Foundation, the Belfer Center for Science and International Affairs, and the Russian Research Center “Kurchatov Institute.”

Copyright 2010 President and Fellows of Harvard College

The co-sponsors of this report invite liberal use of the information provided in it for educational purposes, requiring only that the reproduced material clearly cite the source.

Cover Image: A thorium-uranium fuel assembly developed by the U.S. firm Lightbridge (formerly Thorium Power) and the Russian Research Center “Kurchatov Institute” in a collaborative project.

PROJECT ON MANAGING THE ATOM &
RUSSIAN RESEARCH CENTER “KURCHATOV INSTITUTE”

PROMOTING SAFE, SECURE, AND PEACEFUL
GROWTH OF NUCLEAR ENERGY:

NEXT STEPS FOR RUSSIA AND THE UNITED STATES



HARVARD Kennedy School
BELFER CENTER
for Science and International Affairs



Russian Research Center
KURCHATOV INSTITUTE

OCTOBER 2010

TABLE OF CONTENTS

1. The Need for U.S.-Russian Nuclear Cooperation	1
The Energy Challenges of the 21 st Century.....	1
Figure 1.1: Energy Demand By Fuel Type in the Reference Scenario.....	2
Figure 1.2: Carbon Avoidance “Wedges”	4
The Potential Role of Nuclear Energy.....	5
Figure 1.3: Change in Construction Pace Required for Significant Nuclear Climate Role....	7
A Common Vision	9
The Role of Russia and the United States	9
The Value of the U.S.-Russian Nuclear Cooperation Agreement	13
<i>Benefits of a U.S.-Russian Nuclear Cooperation Agreement</i>	13
<i>Arguments For and Against the 123 Agreement</i>	14
SECTION I: LAYING THE FOUNDATION FOR NUCLEAR GROWTH.....	17
2. Preventing Nuclear Accidents	19
Strengthening Nuclear Regulation.....	20
Strengthening Safety Culture	21
Finding and Fixing the Least Safe Facilities Worldwide	21
Achieving Binding Global Nuclear Safety Standards	22
Designing the Next Generation of Reactors for High Safety Standards	23
Strengthening Reporting and Other Elements of the Global Safety Regime	24
3. Preventing Nuclear Terrorism.....	25
A New Presidential Nuclear Security Initiative.....	25
Effective Global Nuclear Security Standards and Agreements	26
Consolidating and Reducing Stockpiles.....	27
Security Culture.....	29
Expanded International Nuclear Security Cooperation	29
<i>Resources: Extending the Global Partnership</i>	29
<i>Frameworks for Cooperation</i>	30
Deterring Nuclear Theft, Smuggling, and Sabotage	30
4. Preventing Nuclear Proliferation.....	33
Reducing Proliferation Dangers in Iran and North Korea	35
<i>North Korea</i>	35
<i>Iran</i>	36
Strengthening Safeguards.....	37
Stopping Black-Market Nuclear Networks	38
Civilian Employment for Former Weapons Scientists	40
Limiting the Spread of Enrichment and Reprocessing Facilities.....	40
The Importance of the Back End of the Nuclear Fuel Cycle.....	42
Internationalizing the Nuclear Fuel Cycle	42

4. Preventing Nuclear Proliferation (cont)	
More Proliferation-Resistant Approaches to Nuclear Energy	44
Strengthening Enforcement	45
Reducing Demand for Nuclear Weapons	46
Fulfilling the Promise of Article VI	46
 SECTION II: DEVELOPING AND DEPLOYING THE NEXT GENERATION OF NUCLEAR ENERGY	 49
 5. Reducing Nuclear Costs and Bottlenecks	 51
 6. Making Nuclear Energy Broadly Available	 53
A New International Consortium for “Cradle-to-Grave” Nuclear Services.....	53
 7. Making Nuclear Energy Available for a Broader Array of Purposes	 57
 8. Fueling Nuclear Growth	 59
 9. Managing Nuclear Wastes	 63
 10. Areas for Joint R&D	 65
Advanced Modeling and Simulation Technologies	65
Reduced Nuclear Energy Costs	65
Factory-Built Reactors for Widespread Deployment	66
Open-Cycle and Closed-Cycle Approaches to Extending Resources	66
Waste Management and Geologic Disposal	67
High-Temperature Gas-Cooled Reactors (HTGRs)	68
Molten Salt Reactors	68
Reactors for Additional Purposes Beyond Electricity Generation	69
Research on New Regulatory Approaches for Innovative Reactors	69
Advanced Safeguards and Security Technologies	69
 11. Next Steps in U.S.-Russian Nuclear Cooperation	 71

1. THE NEED FOR U.S.-RUSSIAN NUCLEAR COOPERATION

At their April 2009 summit, Russian President Dmitri Medvedev and U.S. President Barack Obama said: “Together, we seek to secure nuclear weapons and materials, while promoting the safe use of nuclear energy for peaceful purposes.” The two presidents agreed that they sought “to promote international cooperation in the peaceful use of nuclear energy while strengthening the nuclear non-proliferation regime.” At their July 2009 summit, they repeated these objectives, and established a joint Nuclear Energy and Nuclear Security Working Group co-chaired by Sergei Kirienko, Director-General of the Russian State Atomic Energy Corporation (Rosatom), and Daniel Poneman, U.S. Deputy Secretary of Energy. This report is intended to provide recommendations for steps Russia and the United States can take to achieve these common goals.

This report proceeds as follows. First, we outline the energy challenges the world faces in the 21st century, the potential role of nuclear energy in addressing these challenges, and the issues that must be addressed if nuclear energy is to play a major role in meeting the world’s 21st century energy needs. Second, we describe the special role that Russia and the United States can play in the future of nuclear energy. We then outline recommended steps Russia and the United States can take to address issues related to: safety; security; nonproliferation; extending uranium resources; waste management; cost reduction; and making nuclear energy more broadly available around the world, and more capable of addressing multiple needs. We describe particular areas of joint research and development that should be undertaken, and the need to move forward with the bilateral Agreement for Cooperation in the Field of Peaceful Uses of Nuclear Energy, to provide a government-to-government framework for this cooperation.

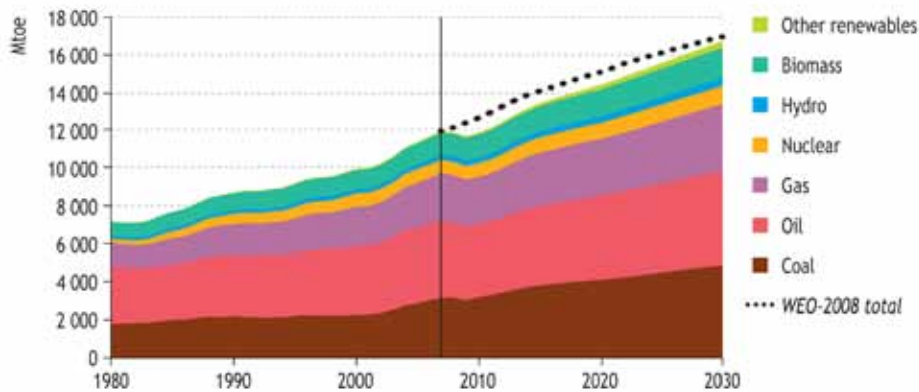
The Energy Challenges of the 21st Century

The world faces three immense and interlinked energy challenges in the 21st century:

- *Availability:* Providing affordable and reliable energy supplies to meet surging global demand (coming from rising populations and growing economies), in a world in which at some point production of oil, the world’s largest energy source, will peak and begin to decline.
- *Environmental impact:* Providing these ever-larger supplies of energy while drastically reducing emissions of heat-trapping gases, to avoid catastrophic climate disruption, and limiting the other impacts of energy extraction and use, which are the biggest environmental problems at local, regional, national, and global scales.
- *Security:* Providing energy supplies that cannot easily be disrupted or suffer devastating price surges, at a time when remaining oil reserves in particular will be increasingly concentrated in the world’s most geopolitically unstable regions.

Meeting all of these challenges simultaneously will be one of the most difficult problems facing humankind in this century. Yet affordable and reliable energy supplies are absolutely essential to modern economies – and expanding those supplies will be a critical element of lifting billions of people out of abject poverty. Today, an estimated 2.4 billion people, more than a third of the world’s population, relies on wood, charcoal, and dung as their principal energy sources, and an estimated 1.6 billion have no access to electricity.

Figure 1.1:
Energy Demand By Fuel Type in the Reference Scenario



Source: International Energy Agency, *World Energy Outlook 2009*

With a growing world population and growing economies, the latest scenarios expect the global primary energy consumption to grow 1.5–3 times by 2050, and 2-5 times by 2100, while the expected growth of electricity consumption could be twice as high.

This surging global demand is a logical result of the increasing integration of the economies of densely populated developing countries into the global economy. Most of the projected growth in energy demand is in developing countries, and their total demand will eventually surpass that of today's developed countries.

Today, some 80% of the world's energy supply comes from burning fossil fuels, which is the largest contributor to emissions of heat-trapping gases, with oil providing the single largest contribution to global energy supply. Fossil fuels are likely to provide most of the world's supply for decades to come. Indeed, despite projected growth in renewable energy supplies, in its "reference scenario," the International Energy Agency expects the use of cheap but environmentally devastating coal to grow faster than any other energy source in the decades ahead. See Figure 1.1.

This ever-growing reliance on burning fossil fuels simply cannot be sustained – the economic, security, and environmental costs will all prove to be unacceptably high. Indeed, it may simply not be possible to meet growing projected demands for oil and gas at acceptable cost. While there is debate over when "peak oil" will occur, there is little debate that at some point in the decades to come, oil production will stop growing and eventually decline, even as energy demand continues to grow. Price spikes, supply disruptions, and political tensions over scarce supplies are likely to become increasingly common. Some countries without oil supplies are becoming increasingly dependent on imports of these scarce resources. The need to develop alternatives that can be deployed at a massive scale – especially for transportation fuels – is real and urgent.

At the same time, there is a growing scientific consensus that to avoid catastrophic climate disruption, steep reductions in global emissions of heat-trapping gases, perhaps in the range of 50% below today's levels, must be achieved by roughly 2050. And climate change is not the only

environmental impact from burning fossil fuels: from acid rain to particulates that pose the largest environmental cause of death and disease, the non-climate environmental impacts of energy use are already devastating and will get dramatically worse if the world continues with current approaches to energy production use.

As the International Energy Agency has put it: “Current global trends in energy supply and use are unsustainable – environmentally, economically, socially.... It is not an exaggeration to claim that the future of human prosperity depends on how successfully we tackle the... central energy challenges facing us.... What is needed is nothing short of an energy technology revolution.” To meet the challenges, both major innovations in energy technology and new international policies and institutions will be needed. Broad international cooperation will be essential, applying common efforts to provide long-term energy supplies for humanity as a whole: no separate solution implemented within a single country or even region will suffice.

The global energy system is huge, and the scale of what must be done to meet these challenges is staggering. The International Energy Agency estimates that simply maintaining “business as usual” will require \$26 *trillion* in energy-related investments between now and 2030. To begin getting on to a path to stabilize long-term concentrations of greenhouse gases in the atmosphere at 450 parts per million of CO₂-equivalent would require an additional \$10.5 trillion in global energy investments by 2030.

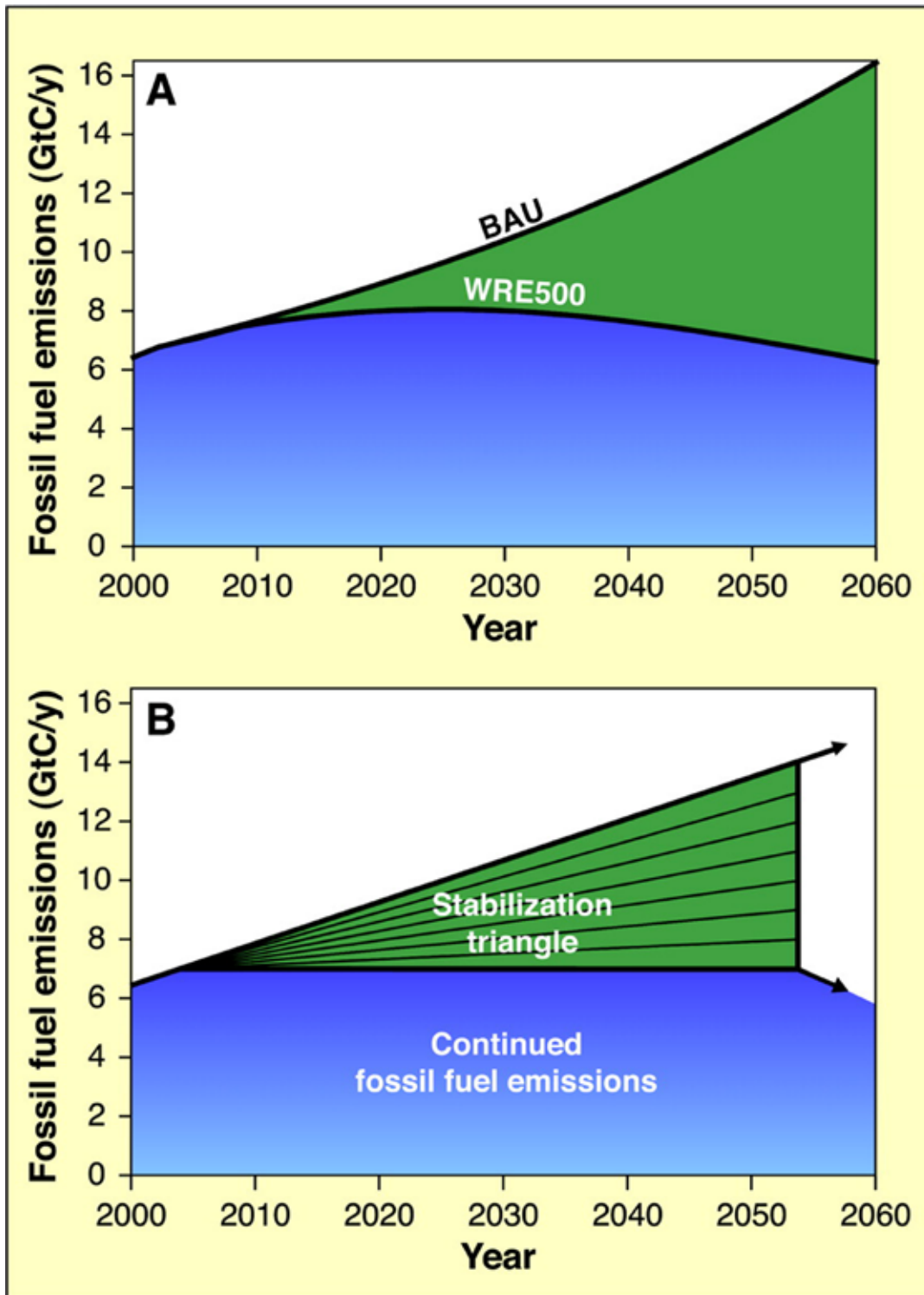
As one way of understanding the scale of the climate problem in particular, analysts from Princeton University have offered an approach that describes what would have to be done to stabilize atmospheric concentrations of carbon dioxide (CO₂) at 500 parts per million (ppm) as a triangular, ever-increasing gap between the “business as usual” emissions trajectory and the emissions that would make it possible to stabilize concentrations at this level. To stabilize atmospheric CO₂ concentrations at this level, they estimate that global emissions in 2050 would have to be reduced by 7 billion tons of carbon per year compared to the “business as usual” level. This could be done by deploying 7 “wedges,” each of which represents a technology that grows enough to avoid the emission of one billion tons a year of carbon by 2050. See Figure 1.2.

Each of these wedges would have to be massive: increasing the fuel economy of two billion cars from 30 to 60 miles per gallon, for example, would provide one wedge, as would deploying two million 2-megawatt-electric (MWe) wind turbines that displaced coal plants.¹ Yet the latest science suggests that 10-15 wedges, rather than seven, may be required – because a lower atmospheric concentration of heat-trapping gases may be required to avoid unmanageable climate disruption, business-as-usual emissions are rising faster than expected, and global “sinks” that remove such gases from the atmosphere appear to be weakening.²

1 Pacala and Socolow, “Stabilization Wedges.”

2 To have a good chance of meeting the goal agreed at Copenhagen of avoiding temperature increases of more than 2° C would require stabilizing atmospheric concentrations at roughly 450 ppm of CO₂-equivalent, significantly less than Pacala and Socolow envisioned. Yet the growth rate of global emissions has tripled compared to the growth rate in the 1990s, opening a much larger gap between business-as-usual emissions and the emissions required for stabilization at 450 ppm than previously projected. See Michael R. Raupach, Gregg Marland, Philippe Ciais, Corinne Le Quéré, Josep P. Canadell, Gernot Klepper, and Christopher B. Field, “Global and Regional Drivers of Accelerating CO₂ Emissions,” *Proceedings of the National Academy of Sciences (U.S.)*, Vol. 104, No. 24 (12 June 2007), pp. 10288-10293. For a discussion of weakening carbon sinks, see, for example, Corinne Le Quéré, Christian Rödenbeck, Erik T. Buitenhuis, Thomas J. Conway, Ray Langenfelds, Antony Gomez, Casper Labuschagne, Michel Ramonet, Takakiyo Nakazawa, Nicolas Metzl, Nathan Gillett, and Martin Heimann, “Saturation of the Southern Ocean CO₂ Sink Due to Recent Climate Change,” *Science*, Vol. 316 (22 June 2007), pp. 1735-1738.

Figure 1.2:
Carbon Avoidance “Wedges” Needed to Stabilize
Atmospheric Concentrations of CO₂ at 500 ppm



S. Pacala and R. Socolow “Stabilization Wedges,” *Science*, Vol. 305, 13 August 2004, p. 969.

The Potential Role of Nuclear Energy

The scale of these challenges is so immense, and the problems, constraints, and uncertainties surrounding every energy technology are so large, that the world must pursue every available low-carbon energy option, including efficiency, renewables, fossil fuels with sequestration of carbon dioxide, and nuclear power. None of these technologies, including nuclear power, can solve these challenges on its own. But as a readily expandable source of low-carbon baseload electricity – and, in the future, hydrogen and heat for other purposes – nuclear energy could be an important part of the answer. Nuclear power is so far the only proven, non-intermittent, readily expandable energy source which is already deployed on a large scale.

Today, nuclear energy is experiencing a substantial revival. Large new reactor construction programs are underway in China, India, and Russia. New reactor construction is planned in the United States for the first time in decades. Several countries in Europe are building or considering new nuclear power plants. And dozens of countries around the world are considering building nuclear power plants for the first time.³

Currently, nuclear energy is used for electricity generation, but both electricity and other applications could contribute to driving future growth. Heat from nuclear power could be used for industrial applications (including refining and many others), hydrogen production, and desalination, displacing fossil fuels that would otherwise be used for these purposes. High-temperature reactors are likely to be especially well-suited for these industrial applications.⁴ Moreover, as plug-in hybrid and electric vehicles achieve larger market shares in the decades to come, electricity from nuclear power and other sources may displace an increasing share of petroleum used for transportation fuel.

For nuclear energy to play a major part in meeting the energy challenges of the 21st century would require a dramatic expansion from today's use of nuclear power. Consider two potential scenarios for large-scale nuclear growth.⁵ In the first, 700 GWe is added to global nuclear power capacity by 2050, bringing the total to some 1070 GWe (roughly tripling current capacity). This would displace roughly a billion tons of carbon emissions every year by that time, one of the needed climate stabilization wedges.⁶ The existing reactors will have to be replaced by then as

3 For an overview, see International Atomic Energy Agency, *International Status and Prospects of Nuclear Power* (Vienna: IAEA, 2009).

4 Many industrial process heat applications require high temperatures. Contemporary high-temperature reactors can reach temperatures in the range of 800°C, but super-high-temperature reactors now under development are expected to produce process heat with temperatures up to 1100°C, if relevant materials challenges can be resolved. Various process heat applications include: desalination (200°C); oil refining (400°C); oil extraction from tar sands (600–700°C); synthetic fuel production from CO₂ and hydrogen (600–1000°C); hydrogen production (600–1000°C); and coal gasification (900–1200°C).

5 These scenarios roughly parallel what are described as the “low growth” and “high-growth” scenarios in IAEA, *International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO): 2009 Progress Report* (Vienna: IAEA, 2009), pp. 18–20. “Low growth” is not a good description of either of these scenarios, however, as both would involve a dramatic increase in the pace of growth of nuclear power. Indeed, the lower of the two scenarios in this study is double the NEA's 2009 low growth scenario, and only modestly below their high-growth scenario (which envisioned a maximum of 1400 GWe in 2050); the higher of the two scenarios in this report is more than 40% above the NEA's high-growth scenario by 2050. See NEA, *Nuclear Energy Outlook*, pp. 18–20. A 2010 study from the NEA and the IEA did envision a high nuclear growth scenario reaching 2000 GWe by 2050, matching the high scenario used in this report. See NEA/OECD and IEA/OECD, *Technology Roadmap: Nuclear Energy* (Paris: NEA/OECD and IEA/OECD, 2010), http://www.iea.org/papers/2010/nuclear_roadmap.pdf (accessed 25 July 2010).

6 In fact, for nuclear energy to provide one carbon-stabilization “wedge” requires 700 GWe *in addition* to whatever nuclear plants would be deployed in a “business as usual” scenario. Pacala and Socolow do not provide any detail concerning the specific

well, meaning that some 25 reactors would have to be built around the world every year from now until 2050. There is no possibility that so many reactors will be built in the next few years, given the costs and difficulties of building nuclear power plants and the limited capacity of the global nuclear industry. Hence, toward the end of the period, the pace would have to be even higher, perhaps in the range of 30-50 reactors every year. A similar pace of construction was achieved briefly in the 1970s; future construction would have sustain and eventually surpass the peak nuclear construction of the past. A recent report of the OECD's NEA and IEA, explored a similar scenario in which the nuclear power sector grew to 1200 GWe by 2050, representing 24% of the total electricity generated worldwide.⁷ Cumulative global investments required to build that much nuclear capacity were estimated at \$4 trillion in today's dollars, or 19% of the \$21 trillion investment in electricity capacity they estimate to be needed by 2050 to meet their proposed climate stabilization target.

In the second scenario, increasing concerns over the environmental impacts and availability of fossil fuels, combined with positive developments for nuclear energy – such as greatly reduced costs and politically sustainable solutions to managing nuclear waste – drive even faster nuclear growth, to 2000 GWe by 2050. To achieve that level would require average annual construction of 50 1-GWe reactors from now until 2050, probably meaning that something in the range of 100 reactors a year would have to be connected to the grid toward the end of the period. By that time, nuclear energy would be providing some 10% of global primary energy supply (likely including both electricity and other products), and would be displacing well over 2 billion tons of carbon emissions per year compared to a “business as usual” scenario – corresponding to something in the range of one-quarter of the solution to the climate part of the energy challenge.

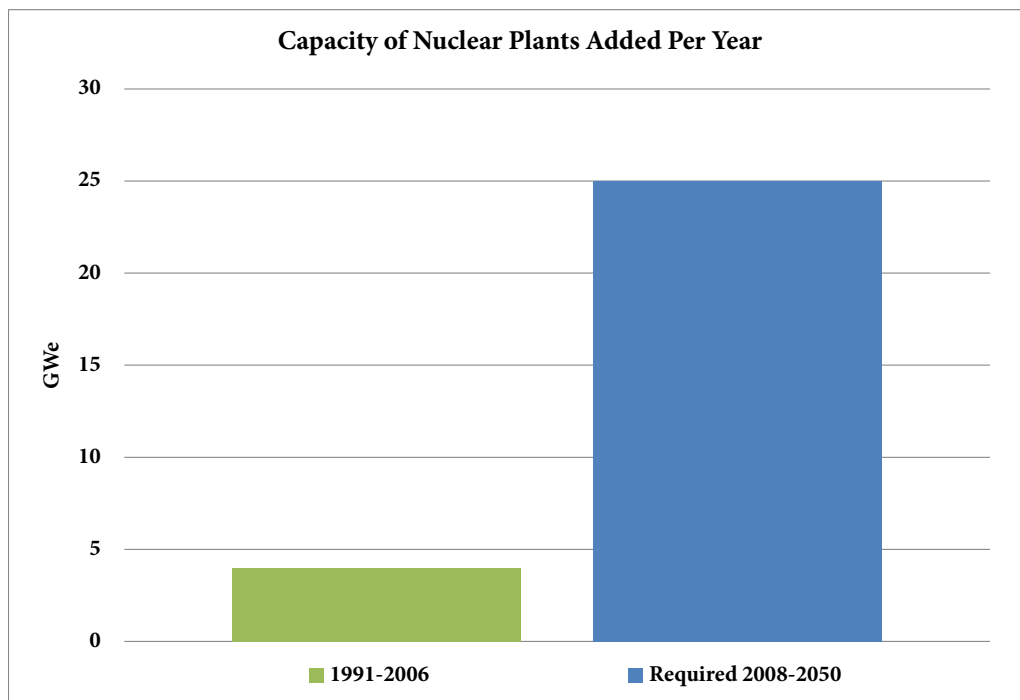
Nuclear growth on these scales implies nuclear spread; it is difficult to imagine nuclear energy being attractive enough to convince the countries now using nuclear power to purchase hundreds of additional reactors without other countries wishing to build reactors as well. Indeed, as already noted, dozens of countries that have no nuclear power plants today have expressed interest in establishing a nuclear power program for the first time, including nearly all of the states of the Middle East. New organizational and institutional approaches will be needed to address the proliferation, safety, and terrorism risks of nuclear power in many states that have never managed nuclear energy before – particularly since many of the states now expressing interest in nuclear power have more political instability and lower government and regulatory effectiveness than most of the states using nuclear power today.⁸

By contrast, the average over the past decade was four reactors attached to the grid worldwide each year, even at a time when the nuclear industry has been speaking of a nuclear “revival” or “renaissance.” No reactors were connected to the grid anywhere in the world in 2008, and only technologies that would be deployed in their business as usual scenario, so we have taken existing nuclear capacity as a baseline, but this is a very conservative assumption. In fact, nuclear growth would have to be more rapid than this for nuclear energy to displace a billion tons of carbon from coal-fired generation by 2050.

⁷ *Technology Roadmap: Nuclear Energy*.

⁸ See the data provided in Scott Sagan and Steven E. Miller, “Nuclear Power Without Proliferation?” *Daedalus*, Vol. 138, No. 4 (Fall 2009), pp. 7-18. The two special issues of this journal in Fall 2009 and Winter 2010 provide a useful overview of issues facing the future of nuclear energy and nonproliferation. For a useful overview of different scenarios for global growth and spread of nuclear power and their respective risks, see Harold Feiveson, Alexander Glaser, Marvin Miller, and Lawrence Scheinman, *Can Future Nuclear Power be Made Proliferation-Resistant?* (College Park: Center for International Security Studies at Maryland, School of Public Policy, University of Maryland, July 2008), http://www.cissm.umd.edu/papers/files/future_nuclear_power.pdf (accessed 15 June 2010).

Figure 1.3:
Change in Construction Pace Required for Significant Nuclear Climate Role



two were connected in 2009.⁹ To shift to 25-50 reactors per year – which is essential for nuclear energy to play more than a marginal role in meeting the energy needs of the 21st century – nuclear energy would have to become dramatically more attractive to utilities, governments, and publics around the world. This would require:

- Providing sufficient fuel supplies;
- Reducing costs;
- Effectively managing nuclear waste;
- Avoiding major accidents;
- Preventing major nuclear terrorist attacks;
- Averting a cascade of nuclear weapons proliferation;
- Increasing public support and confidence;
- Resolving industry supply-chain bottlenecks (such as current limits on capacity for ultra-large steel forgings and limited availability of trained personnel);
- Making nuclear energy suitable for use by a broader portion of the world's population; and
- Making nuclear energy suitable for a broader array of purposes than simply production of baseload electricity.

These challenges are interconnected and can only be addressed effectively in an integrated

⁹ International Atomic Energy Agency, *Power Reactor Information System* (Vienna: IAEA, 2010), <http://www.iaea.org/programmes/a2/index.html> (accessed 12 June 2010).

fashion. For example, safety and security measures must be both effective and affordable, and waste management options must be politically sustainable, proliferation-resistant, environmentally acceptable, and cost-effective.

In short, nuclear safety, security, nonproliferation, and waste management are essential enablers for large-scale nuclear energy growth. It is very much in the world's interest – and the nuclear industry's interest – to drive the risk of catastrophes as close to zero as possible.

Current once-through approaches to nuclear energy make use of less than 1% of the energy potential of mined uranium. Fast-breeder reactors with recycling could multiply the resources available to support nuclear fission energy by 60-70 times, and some countries are also pursuing fast-reactor options for enhanced management of nuclear wastes (as discussed later in this report). Commercialization of fast-breeder reactors has been delayed, however, as sufficient uranium fuel has been available to continue reliance on light-water reactors, fast reactors have to date been more expensive than light-water reactors, and fast reactors coupled with traditional reprocessing technologies produce plutonium which is usable in nuclear weapons. World uranium resources are sufficient to support either of the nuclear energy growth scenarios just described for decades to come on a once-through cycle, allowing time for additional research and development on approaches that may be able to reduce the costs and improve the proliferation-resistance of fast reactors and recycling. The most recent assessment of uranium resources from the IAEA and the NEA includes 6.3 million tons of “identified resources” and an additional 10.4 million tons of “undiscovered resources” – resources that countries expect to exist, but have not yet been definitely confirmed. The report concludes that meeting even the requirements for their high-nuclear-growth case “would consume less than half of the identified resources” by 2035 – leaving the remainder of the identified resources and the undiscovered resources still potentially available.¹⁰

Nonetheless, uranium resources are not infinite, and if reliance on fission energy grows rapidly and is sustained for an extended period, eventually widespread deployment of breeder reactors or other means of extending uranium resources may become essential.¹¹ When this will occur depends on the pace of nuclear energy growth and the size of the uranium resources that ultimately prove to be available as a function of price. Results of analyses of nuclear growth scenarios such as those described above carried out at the Kurchatov Institute¹² indicate that the answers are very different for the two scenarios described above. In the moderate-growth scenario (1070 GWe by 2050), there would be enough uranium for the 21st century without widespread deployment of fast reactors and recycling—if issues of spent fuel and nuclear waste management were addressed by other means or postponed (via interim storage technologies) until after the 21st century. In the higher growth scenario (2000 GWe by 2050), a once-through fuel cycle would consume somewhat more than the currently identified uranium resources by 2050, and widespread deployment of new approaches to nuclear energy possibly would be needed, including a closed fuel cycle with fast reactors and possibly also more advanced types of light-water reactors

10 NEA/OECD and IAEA, *Uranium 2009: Resources, Production, and Demand*, pp. 10, 13, and 15-33.

11 In addition to fast reactors with recycling, other concepts for extending uranium resources include a variety of ideas for fast reactors that might be able to breed and burn fuel without reprocessing; thermal systems such as the molten salt reactor, which can breed additional fuel with only partial separation of fission products from the fluid fuel stream (though without the possibility of high breeding ratios); a number of concepts for mixing thorium and uranium in fuel; and concepts for thermal reactors with very high neutron economy and high burnup.

12 E.P. Velikhov, A.Yu. Gagarinski, S.A. Subbotin, V.F. Tsibulski, *Energy Evolution in the XXI Century*, (Moscow: IzdAt, 2008 [in Russian]).

and high-temperature gas-cooled reactors. (The issues in the recycling debate are discussed in more detail later in this report.)

A Common Vision

The authors of this report share a common vision – a vision of Russia, the United States, and other countries cooperating in international efforts aimed at enabling large-scale growth of nuclear energy around the world while achieving even higher standards of safety, security, and nonproliferation than are in place today. Achieving this common vision will require both technical and institutional innovations. It will require building a new global framework for managing nuclear energy, including new or strengthened institutions that can effectively accomplish agreed safety, security, and nonproliferation goals while respecting states' interests in sovereignty and energy security.

If, on the other hand, nuclear energy is pursued *without* stronger measures for safety, security, and nonproliferation, and developed in directions that could undermine these goals, the result could be both grave safety, security, and proliferation risks and an irrevocable erosion of the conditions necessary to achieve and sustain large-scale nuclear growth. Safe and secure operation of nuclear facilities could be undermined, discrediting and thereby postponing the large-scale use of nuclear energy. Even a single catastrophe – whether a Chernobyl-scale accident, a successful sabotage (a “security Chernobyl”), or worse yet, a terrorist nuclear bomb – would severely undermine prospects for nuclear growth on the scale needed to make a significant contribution to coping with climate change. New institutional and technological approaches are not just “nice to have” – they are essential if nuclear energy is to make a major contribution to the energy challenges of the 21st century without posing undue risks.

The Role of Russia and the United States

Today, 30 countries have operating nuclear power plants, and several countries are playing leading roles in the development of new nuclear technologies and approaches. No new nuclear power plant has been built in the United States in decades, and Russia has only returned to building new nuclear power plants in recent years, after a long post-Chernobyl gap. But Russia and the United States still have absolutely central roles to play.

Russia and the United States were the first countries to harness nuclear energy, both for nuclear weapons and for power. The birth of civilian nuclear energy was marked by the first nuclear electricity, obtained in a U.S. nuclear laboratory in 1951, the Atoms for Peace initiative put forward by President Eisenhower in 1953, and the first nuclear power plant, created by Academician Igor I. Kurchatov in the Soviet Union in 1954. For decades, Russia and the United States were the principal suppliers of nuclear reactors, nuclear fuels, and nuclear technologies for the world, and their nuclear establishments served as a model for many other countries.

While both Russia and the United States devoted much of their nuclear expertise to military purposes during the Cold War, both countries simultaneously built up a comprehensive system for nuclear science and engineering, accumulating an enormous amount of knowledge and technological experience in designing, building, and operating nuclear power and nuclear fuel cycle facilities. With Three Mile Island and Chernobyl (and the earlier incident at Kyshtym), the United States and the Soviet Union experienced the world's most serious nuclear accidents, and

subsequently played leading roles in building the international nuclear safety regime. Similarly, the Soviet Union and the United States have played central roles in the global struggle to stem the spread of nuclear weapons since that effort began; together with the United Kingdom, they are the three depositary governments for the Nuclear Nonproliferation Treaty (NPT). Russia and the United States have also worked closely together to keep nuclear weapons and the materials needed to make them out of terrorist hands, with in-depth cooperation on nuclear material protection, control, and accounting (MPC&A) since the early 1990s. U.S. and Russian cooperation to prevent nuclear terrorism accelerated with the joint nuclear security initiative launched at the Bratislava summit in 2005, and moved to another stage in 2006 with the launch of the Global Initiative to Combat Nuclear Terrorism, co-chaired by Russia and the United States. Both countries were key participants in the Nuclear Security Summit in Washington, D.C. in April 2010.

Today, despite the funding cutbacks and difficulties of the 1990s, Russia and the United States have some of the world's largest and most advanced nuclear establishments. The United States has the world's largest number of operating nuclear power reactors, and Russia has one of the world's largest nuclear reactor construction programs. Along with countries such as France and Japan, the United States and Russia continue to maintain some of the world's largest and most active nuclear R&D programs. Russian and U.S. companies continue to play leading roles in the markets for nuclear reactors, fuels, and technologies. The United States and Russia have been strong supporters of international cooperation to develop new nuclear energy technologies. The United States was a key initiator of the Generation IV International Forum (GIF), a global effort to develop the next generation of reactor and fuel cycle systems (which Russia has now joined), and Russia played a leading role in establishing the IAEA's International Project on Innovative Reactors and Fuel Cycles (INPRO), an even broader global effort in which the United States is now participating. Gen. IV and INPRO have transformed the analysis of large-scale nuclear energy development prospects from studies performed by separate groups of scientists in different countries into coordinated activities supported by many countries.

In short, though Russia and the United States are not the dominant nuclear countries they once were, there is no doubt that both Russia and the United States will have to take strong action, separately and together, if there is to be any hope of achieving nuclear growth on the scale required to make a substantial contribution to meeting the energy challenges of the 21st century. In an increasingly globalized nuclear market, the prospects for safe, secure, and peaceful nuclear energy growth will be best if Russia, the United States, and other leading players are all working together toward that end.

Moreover, in recent years, Russia and the United States have undertaken promising cooperation across a broad range of nuclear activities. In addition to the extraordinarily fruitful cooperative work done to dismantle nuclear missiles, bombers, and submarines, improve security for nuclear stockpiles, and strengthen protections against proliferation of sensitive technologies, the two countries have worked together on a broad range of efforts in civilian nuclear energy, including:

- Extensive cooperation to improve nuclear safety, especially in the 1990s, from in-depth safety assessments, to installation of enhanced safety equipment, to exchange of advanced technologies such as approaches to restoration of aging nuclear reactor vessels.

- Central Russian and U.S. roles in large international projects, including not only INPRO and Gen. IV, but efforts such as the RASPLAV Project of the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD), which included a program of extreme experiments performed in Russia to study severe nuclear accidents, or the Criticality Safety Benchmark Project initiated by the United States (which was also undertaken under the auspices of the NEA/OECD).
- Russia and the United States have been jointly developing the Modular High-Temperature Gas-Cooled Reactor (MHTGR), an example of an innovative project in which a joint Russian-U.S. initiative has evolved into an ongoing international program.
- Russia and the United States are also collaborating to develop and test a new generation of thorium-uranium fuels that can be used in existing light-water reactors, and, possibly, in new reactors of other types, extending uranium resources and reducing the amount and quality of the plutonium in spent reactor fuel.
- Russia and the United States are collaborating, along with other countries, to develop and implement new concepts for global approaches to providing nuclear energy around the world while minimizing safety, security, and proliferation risks, including: (a) the Global Nuclear Energy Infrastructure concept put forward by then-Russian President (now Prime Minister) Vladimir Putin (with the first element of that infrastructure being the International Enrichment Center at Angarsk); (b) the Global Nuclear Energy Partnership (GNEP) proposed by then-U.S. President George W. Bush, whose concepts for “cradle-to-grave” fuel services are still being explored in the Obama administration; and (c) a variety of concepts for providing increased assurances of fuel supply, including IAEA-controlled reserves and agreements by the major suppliers to step in if supply from any one supplier is interrupted.
- At the 2006 G-8 Summit in St. Petersburg, the presidents of the Russian Federation and the United States put forward initiatives on global development of safe, secure, and peaceful nuclear energy, and announced the two countries’ intention to cooperate in long-term nuclear energy development.
- As noted at the outset, Russian President Dmitry Medvedev and U.S. President Barack Obama have agreed that the United States and Russia will expand their cooperation on nuclear energy, and established a Nuclear Energy and Nuclear Safety Working Group to move these efforts forward.
- Russian and U.S. non-governmental experts have made significant contributions in supporting government decision-making in these areas. Some of the participants in this study, for example, were also participants in the U.S.-Russian Independent Scientific Commission on Disposition of Excess Weapons Plutonium in 1997;¹³ that report and a meeting of U.S. and Russian government and non-government experts organized at Harvard University helped launch the negotiation of the 2000 U.S.-Russian Plutonium Management and Disposition Agreement, whose protocol was just completed in April 2010.
- Similarly, in 2002, experts led by the Kurchatov Institute in Russia and Sandia National Laboratories in the United States prepared a joint report on the global nuclear future whose recommendations contributed to the renewal of government-to-government cooperation on civilian nuclear energy development.¹⁴

13 Evgeniy P. Velikhov and John P. Holdren, co-chairs, *U.S.-Russian Independent Scientific Commission on Disposition of Excess Weapons Plutonium: Final Report* (Washington, D.C.: Office of Science and Technology Policy, June 1, 1997).

14 Sandia national Laboratories and Russian Research Center “Kurchatov Institute,” *The Global Nuclear Future: From Atoms for*

- In July 2004, the directors of key U.S. and Russian national laboratories met in Vienna and agreed on a joint document outlining a common vision of the contributions that the Russian and U.S. nuclear communities could make to large-scale global nuclear power development.¹⁵
- From 2002-2009, the U.S. and Russian Presidents have repeatedly issued strong statements endorsing cooperation between the United States and Russia in developing new nuclear energy technologies and in making the benefits of nuclear energy available to all, while ensuring safety and controlling proliferation risks. As noted at the outset of this report, Russian President Obama and U.S. President Medvedev have established a joint working group co-chaired by Rosatom Director-General Sergei Kirienko and U.S. Deputy Secretary of Energy Daniel Poneman, which is working out a joint action plan for nuclear energy cooperation.



U.S. President Barack Obama, President Nursultan Nazarbayev of Kazakhstan, Russian President Dmitry Medvedev, and Russian Foreign Minister Sergei Lavrov at the Nuclear Security Summit in April 2010, where they joined with other world leaders in calling for an urgent effort to improve security for nuclear stockpiles around the world. Russia and the United States have a long record of cooperation to improve security and accounting for nuclear stockpiles, and co-chair the Global Initiative to Combat Nuclear Terrorism. Source: White House Photo by Pete Souza

All of this creates a strong foundation for a U.S.-Russian partnership in promoting safe, secure, and peaceful nuclear energy growth. Russia and the United States share vital national interests in preventing nuclear terrorism; stopping nuclear proliferation; avoiding major nuclear accidents; and using nuclear power as a tool to cope with intertwined energy challenges of the 21st century. These vital national interests can best be secured by working together. As the two countries with the longest experience with nuclear power; the two coun-

tries that possess more than 95% of the world's nuclear weapons; the two most critical leaders in founding the nonproliferation regime; and the two countries with the largest establishments of nuclear scientists and engineers, Russia and the United States have a responsibility to take the lead in building a world that enables large-scale growth of nuclear energy while managing its risks. In-depth cooperation will be essential – as will cooperation with other countries that are also now playing leading roles in advancing the technology and management of nuclear energy.

U.S.-Russian nuclear energy cooperation must proceed on the basis of a genuine partnership, incorporating knowledge and ideas from experts on both sides, and with both sides contributing resources to the effort.

Peace to Atoms for Peace and Prosperity (Albuquerque, N.M.: Sandia National Laboratories, 2002).

¹⁵ *Toward a Global Nuclear Future: A Joint Document of the Directors of Russian and U.S. National Laboratories-State Research Centers Concerning Sustainable Nuclear Energy for the 21st Century*, July 2004.

The Value of the U.S.-Russian Nuclear Cooperation Agreement

In the subsequent chapters of this report, we will describe an agenda for a broad range of cooperation between the United States and Russia in the civil uses of nuclear energy can serve both countries' national interests. Through expanded cooperation, Russia and the United States can contribute to improved safety, strengthened security, more effective efforts to stem the spread of nuclear weapons, better waste management, expanded nuclear fuel resources, and a brighter future for nuclear energy as a tool in meeting the energy challenges of the 21st century.

The in-depth cooperation needed must be built not only on shared interests and complementary expertise, but also on an appropriate legal framework to facilitate the effort. We strongly recommend, therefore, that the U.S. and Russian governments take action to bring the U.S.-Russian agreement on peaceful nuclear cooperation – known as the “123 Agreement” after the relevant section of the U.S. Atomic Energy Act – into force as soon as possible.

The U.S.-Russian 123 agreement was completed in 2008, but because of the political tensions over the conflict between Russia and Georgia in August 2008, the Bush administration withdrew the agreement from Congressional consideration (for fear that in that atmosphere it would be voted down), and it has not yet entered into force. On 10 May 2010, President Obama resubmitted the agreement to Congress. As part of the ongoing “reset” of U.S.-Russian relations, it is time to complete the process of bringing this agreement into force.

Benefits of a U.S.-Russian Nuclear Cooperation Agreement

Under U.S. law, a 123 agreement is required for any cooperation that involves transferring U.S.-origin nuclear materials, reactors, or major components to Russia (including transfers of materials from other countries that have been irradiated in U.S.-design nuclear reactors). Under current Russian law and policy, cooperative projects in the nuclear sphere and visits to nuclear facilities must proceed under the authority of a government-to-government agreement, and for many potential cooperative projects, no relevant agreements are yet in place.

As a result, without such a 123 agreement in place, a wide range of beneficial cooperation is being slowed or cannot move forward. Without such an overall umbrella for cooperation, each proposed type of cooperation often requires a separate government-to-government agreement, substantially slowing joint efforts. In many cases, U.S. scientists cannot even visit nuclear sites to discuss ideas for cooperation if there is no government-to-government agreement for that cooperation in place; many potentially promising projects have been stymied by such restrictions, as have the serendipitous ideas that often develop when scientists are able to meet and work together on their actual facilities. Moreover, without such an overall umbrella agreement authorizing cooperation, scientists are often uncertain as to how far cooperation can legally proceed – either under U.S. law or under Russian law – and natural caution results in many perfectly legal efforts being slowed or stopped. Scientists should be able to cooperate in unclassified areas without needing to worry about such legal matters.

Of course, cooperation in areas such as improving security for nuclear materials and reemploying former weapons scientists in civilian pursuits has been underway for years, under the authority of existing agreements such as the Nunn-Lugar implementing agreement. And some

forms of scientific research on nuclear energy can proceed even without an agreement. So it is clearly not the case that *no* cooperation can proceed until the 123 agreement is in force.

But having a 123 agreement in place would enable a much wider range of cooperation, including:

- Commercial cooperation between U.S. and Russian firms in reactor design and sales (potentially important in an increasingly globalized market featuring competition among international alliances of major nuclear firms);
- Joint design and development of new reactor and fuel cycle approaches;
- U.S. transfer to Russia of nuclear materials or components for testing in Russian experimental facilities (which are more extensive in a number of areas than those still maintained in the United States);
- Establishment of a multinational consortium with both Russia and the United States as key participants, providing “cradle-to-grave” reactor services based on factory-built reactors with high levels of inherent safety, security, and proliferation-resistance (a potentially important initiative for both nuclear energy and nonproliferation, described in more detail in Chapter 5);
- Other approaches to full fuel-cycle services that would involve shipment of spent fuel that was U.S.-origin or had been irradiated in U.S.-origin reactors from third countries to Russia;
- Cooperation in areas that have no government-to-government agreement at present, such as on consolidating nuclear material in fewer locations to improve security;¹⁶ and
- More comprehensive and effective scientific cooperation on nuclear energy, not constrained by real or perceived legal barriers to cooperation.
- These types of cooperation could have important benefits for both nuclear energy and non-proliferation.¹⁷

Arguments For and Against the 123 Agreement

In the United States, the main motivation for opponents of the U.S.-Russian 123 agreement is Russia’s cooperation with Iran in building the Bushehr nuclear reactor. Some in the U.S. Congress and elsewhere have argued that the United States should not proceed with the agreement until Russia ceases its nuclear cooperation with Iran. Several points should be made in this context:

- First, it is important to understand that what Russia is building in Iran is a light-water reactor (LWR), under IAEA safeguards, which is not a part of Iran’s suspected nuclear weapons effort.
- Russia has cut off several other sensitive nuclear or dual-use transfers, and has pledged not to transfer sensitive technology that would be helpful in a nuclear weapons program to Iran.

¹⁶ Russia and the United States have been cooperating for years in the Material Consolidation and Conversion (MCC) effort, but the Russian government has made clear that expanding this cooperation requires a formal government-to-government agreement of some kind. As of this writing (July 2010) efforts to negotiate a separate agreement for MCC have not been successful.

¹⁷ For a comprehensive assessment that strongly supports moving forward with the agreement, see Robert Einhorn, Rose Gottemoeller, Fred McGoldrick, Daniel Poneman and Jon Wolfsthal, *The U.S.-Russia Civil Nuclear Agreement: A Framework for Cooperation* (Washington, D.C.: Center for Strategic and International Studies, May 2008), <http://csis.org/files/media/csis/pubs/080522-einhorn-u.s.-russia-web.pdf> (accessed 4 June 2010).

- Russia has joined with the United States in pressing Iran to suspend its enrichment and reprocessing activities.
- Russia has supported a series of UN Security Council sanctions resolutions against Iran, including a ban on any transfers of nuclear-related technologies that would support Iran's enrichment, reprocessing, or nuclear weapons efforts, and supported the new sanctions resolution approved in June 2010 (UN Security Council Resolution 1929).
- Russia successfully insisted on Iran agreeing to a contract in which all the plutonium-bearing spent fuel from the Bushehr reactor will be returned to Russia, so that a potential plutonium stock will not build up in Iran.

Russia argues that, like the United States, it wants to ensure that Iran never acquires nuclear weapons, but that has a different view of what approaches will be most effective in achieving that objective. Russia has long argued that in-depth negotiation with Iran is likely to be more effective than sanctions in constraining Iran's nuclear ambitions. In that context, Russia contends that its cooperation with Iran on Bushehr enhances its credibility in engaging Iran on the future of its nuclear program – and that argument has some merit. Russia points out that the United States, Russia, and the other members of the P5+1 have agreed that they would support Iran's use of nuclear energy if Iran comes into compliance with its nonproliferation obligations and UN Security Council requirements, specifically indicating that under those circumstances they would cooperate on reactors such as the one being built at Bushehr – though the United States would prefer that such cooperation not proceed until Iran has come into compliance with Security Council resolutions.

Russia has cooperated with the United States in blocking a number of transfers of nuclear and missile technology to Iran over the last two decades (though some illicit transfers occurred in the past), and has committed not to transfer sensitive nuclear technologies to Iran. Implementation of Russia's pledge not to carry out sensitive transfers to Iran will be important. Russia and China have both resisted stronger sanctions against Iran that the U.S. government and other members of the P5+1 believe should be imposed. But there is little merit in blocking nuclear cooperation that serves both U.S. and Russian national interests because of a difference of view over the best approach to convincing Iran to abandon its nuclear weapons ambitions – particularly as the real but limited benefits to Russia of nuclear cooperation with the United States are not likely to be enough to change Russia's perspective on Iran.

From a U.S. perspective, it is important to remember that the agreement, as written, is not self-executing. Each additional transfer of nuclear material or technology will require a separate government approval. Hence it is not the case that approving the agreement would commit the United States to approving transfers regardless of Russia's future policy on Iran.

Indeed, a strong argument can be made that the probability that Russia will adopt approaches to the issue of Iran's nuclear program that the U.S. government finds constructive will be higher if the United States approves the 123 agreement and thereby launches a stronger, ongoing structure and habit of cooperation between Russia and the United States on nuclear issues than it will be if the United States rejects the agreement and walks away from cooperation. There will be little chance of resolving the crisis over Iran's nuclear program unless Russia, the United States, and other members of the P5+1 are working closely and cooperatively together.

Other U.S. opponents of the U.S.-Russian 123 agreement have raised concerns over issues raised during the August 2008 conflict with Georgia, or over Russia's overall political direction. But those are political disagreements in which neither the Russian nor the U.S. nuclear establishments are remotely involved; they have nothing to do with the merit of U.S.-Russian nuclear cooperation, and rejecting such cooperation will not contribute to resolving them.

Others have argued that the 123 agreement would only benefit work on reprocessing and fast reactors, and since they oppose such work, they oppose the 123 agreement. As should be clear from the discussion above, entry into force of the 123 agreement would benefit a much broader spectrum of cooperation. Moreover, R&D to explore whether the problems of past reprocessing and fast reactor technologies can be overcome would benefit both Russia and the United States.

Fundamentally, the issue is whether, in a globalized world with a growing demand for nuclear energy and growing risks of nuclear proliferation and terrorism, the world's two largest nuclear enterprises should be working together cooperatively or not. The answer seems clear. The reality is that Russia's nuclear complex controls vast stores of nuclear weapons, materials, technologies, and experts whose fate affects vital U.S. and international interests. Much the same can be said about how the fate of the U.S. nuclear enterprise affects Russian interests. For better or for worse, in Russia the 123 agreement has come to be seen as an important symbol of whether the United States is serious about mutually beneficial cooperation with Russia's nuclear complex or not. A Russian conclusion that the answer was "no" would endanger a broad range of U.S. interests. U.S.-Russian nuclear cooperation and engagement serves both countries' national interests far better than mutual isolation and hostility.

Russia and the United States should:

- Work together to make the case in the U.S. Congress for the broad range of benefits to U.S. interests, international security, and the future of nuclear energy that could result from expanded cooperation under the 123 agreement.
- Take action to bring the 123 agreement into force as rapidly as practicable.
- Build a broad structure of cooperation to promote safe, secure, and peaceful growth of nuclear energy, as described in this report.

This report proceeds as follows. Section 1 identifies steps Russia and the United States can take to create the conditions for sustainable large-scale nuclear growth, including providing for safety, security, and nonproliferation. Section 2 outlines additional steps Russia and the United States can take to develop and deploy the next generation of nuclear technologies, from reducing costs and improving management of wastes to making nuclear energy broadly available to countries around the world in ways that would not increase proliferation risks. The report then concludes with a brief chapter summarizing recommended next steps in nuclear cooperation between Russia and the United States.

SECTION I: LAYING THE FOUNDATION FOR NUCLEAR GROWTH

2. PREVENTING NUCLEAR ACCIDENTS

Large-scale growth of nuclear energy depends on convincing publics around the world that nuclear power will be safe – including not only the operation of power reactors, but the management of spent nuclear fuel and radioactive wastes as well – and that nuclear power offers significant environmental advantages compared with fossil energy technologies.

Based on long experience in the design, development, construction and operation of nuclear power plants and other nuclear facilities, and taking account of the lessons of the Three Mile Island and Chernobyl accidents, the international nuclear community has developed a set of common practices and approaches to safety – outlined in International Atomic Energy Agency (IAEA) documents – based on the fundamental principle of defense in depth.

In this approach, nuclear plants should have multiple, reliable safety features, so that the failure of any one element cannot lead to a major accident. In recent years, the trend is toward increased use of passive means of preventing accidents, which do not rely on equipment such as pumps that could fail. While the plant's safety features are central, the human factor – a workforce with a strong safety culture, who continuously concentrate on safe operation and are vigilant in identifying and addressing any issues that arise – is also essential. Prevention of accidents is the first priority, a complete approach to safety must also include measures intended to mitigate the consequences should an accident occur.

Measures taken by the world nuclear community have made nuclear power plants far safer today than they were in the days of Three Mile Island and Chernobyl. Unfortunately, nuclear plants' capital costs have also increased, in part as a result of a wide range of additional safety and security features. But the risk of a major accidental release of radioactivity is not zero. Any such accident would not only be a catastrophe for the region where it occurred, but would provoke political reactions that would severely undermine prospects for a large-scale expansion of nuclear power. To expand nuclear power to 3-10 times its current energy contribution without increasing the risks of a major accident will require meeting still higher standards of nuclear safety around the world.¹⁸

Russia and the United States should seek to be world leaders in nuclear safety, settling for nothing less than excellence. Each country should establish a culture and policy of continual improvement in nuclear safety, focusing attention on reducing the most significant remaining risks. Russia and the United States should cooperate in helping other countries do likewise. Some countries are now at an important turning point in launching nuclear energy programs for

18 For somewhat similar arguments to those of this section, see Commission of Eminent Persons, Reinforcing the Global Nuclear Order for Peace and Prosperity: The Role of the IAEA to 2020 and Beyond (Vienna: International Atomic Energy Agency, May 2008), <http://www.iaea.org/NewsCenter/News/PDF/2020report0508.pdf> (accessed 8 June 2010). See also International Nuclear Safety Advisory Group (INSAG), Strengthening the Global Nuclear Safety Regime, INSAG-21 (Vienna: International Atomic Energy Agency, 2006). A very useful summary of recent activities can be found in International Atomic Energy Agency, Nuclear Safety Review for the Year 2007, GC(52)/INF/2 (Vienna: IAEA, July 2008), http://www.iaea.org/About/Policy/GC/GC52/GC52InfDocuments/English/gc52inf-2_en.pdf (accessed 3 July 2009).

the first time, and it is essential to put in place effective approaches to nuclear safety as they do so, to avoid accidents that could discredit the use of nuclear energy around the world.

Today, nuclear power designs are intended both to prevent accidents and to mitigate the consequences of any accidents that do occur. It is an accepted international principle that nuclear safety should include defense-in-depth, so that the failure of any one safety system does not lead to a catastrophic accident. The trend is toward ever-greater use of passive approaches, which do not rely on humans to take instant action or pumps to perform properly in

order to maintain safety. Safety assessments must include not only accidents in which the reactor core remains intact, but also beyond-design-basis accidents which lead to serious core damage, up to and including melting of the fuel and collapse of the core, and designs should ensure that even in that case, no major release of radioactivity results.

The future of nuclear energy depends not only on technical and organizational measures for nuclear safety, but on public perceptions and public confidence. The nuclear industry must engage in an ongoing dialogue with the public and address public concerns in an open and transparent way. It is important to make the case that overall, the environmental impacts and risks from nuclear energy are lower than those of fossil energy alternatives; tens of thousands of people every year, for example, die as a result of particulates released from coal burning. Russia's official policy that no nuclear plant will be built in an area that does not want it is a major step in the right direction.

Strengthening Nuclear Regulation

Effective nuclear regulation is an essential element of a strong nuclear safety system. Russia and the United States should provide their nuclear regulators with the resources, expertise, authority, and independence they need to be effective in ensuring that all nuclear activities are conducted safely.

The U.S. Nuclear Regulatory Commission (NRC) and Rostekhnadzor should expand sharing of experience, best practices, and discussion of mutual problems, helping each to learn from the experiences of the other. This should include joint participation or observation in inspections at civilian nuclear power plants.



A football-sized hole in the pressure vessel head of the U.S. Davis-Besse nuclear plant almost led to a large loss-of-coolant accident. Such incidents make clear that even the countries with the most nuclear experience need to continuously struggle to strengthen safety culture. To keep accident risks from rising as nuclear power grows around the world will require achieving ever-higher standards of safety, requiring new technical and institutional approaches.

Source: FirstEnergy

Russia and the United States, working with other countries and the International Atomic Energy Agency (IAEA), should work to help other countries establish effective nuclear regulatory systems or strengthen their existing regulatory approaches. Establishing effective nuclear regulation in “newcomer” states building their first nuclear power plants will be particularly important.

Strengthening Safety Culture

Forging strong safety cultures – the habit among all personnel of giving safety top priority – is essential to achieving high nuclear safety performance. The staff of nuclear facilities can be a source of both hazardous events and stabilizing actions and measures. Safety culture should minimize the former and maximize the latter.

The Davis-Besse incident in the United States – in which inspections were delayed until dripping boric acid had eaten away a football-sized hole in the reactor pressure vessel, leaving only a centimeter of steel remaining to prevent a massive loss of coolant accident – is a reminder that safety culture requires continuous attention and can be a serious problem even in the most advanced nuclear countries.

The United States and Russia should each seek to strengthen nuclear safety culture in their countries through expanded training, incentives for good performance, and management leadership focused on getting all personnel to make safety a top priority every day. They should establish regular programs to assess safety culture and efforts to improve it at each major nuclear facility, and in their nuclear regulatory agencies. These efforts must include an intense focus on building a “reporting culture,” in which all staff are encouraged to report and resolve all problems that arise that could have an effect on safety.

Finding and Fixing the Least Safe Facilities Worldwide

A small number of the least safe facilities dominate the global risk of a major nuclear accident. To reduce that risk, it is crucial to strengthen institutions that will make it possible to find and fix these least-safe facilities. Plants that are likely to be of particular concern include:

1. Older reactors lacking modern safety features;
2. Reactors in “newcomer” states that have not yet developed sufficient experience in implementing effective nuclear safety regulation or building strong safety cultures; and
3. Plants with poor safety culture, which may occur in any country, as just discussed.

Russia and the United States should work together to address each of these categories of risk. In particular, ensuring nuclear safety globally will require strong global institutions. Russia and the United States should work together to strengthen the safety role of the IAEA; to ensure that the World Association of Nuclear Operators (WANO) is as effective as it can be, and carries out in-depth peer reviews at each member facility, while sharing and analyzing information on all safety-related incidents at each member facility; and that other elements of the international nuclear safety regime are also strengthened.

Older reactors lacking modern safety features. Russia and the United States should take special safety measures at their older reactors, to ensure that for as long as they continue to oper-

ate, these reactors pose no higher risk of a major radioactive release than newer reactors do. Each country should shut down any reactors that cannot meet this standard. Russia and the United States, as the suppliers of nearly all of the world's oldest reactors, should work with other countries to ensure that they take similar actions to address the risks posed by these older facilities.

Achieving high standards of safety in newcomer states. The United States, Russia, the IAEA, and other advanced nuclear countries should work intensely with “newcomer” states to help them establish effective safety infrastructures before building nuclear plants, including effective nuclear regulatory systems and strong nuclear safety cultures. Small or medium-sized reactors with high levels of inherent safety, as discussed earlier, could be a particularly attractive option for newcomer states. As discussed in detail in a later chapter, the United States and Russia should work together to explore whether, and how rapidly, such reactors can be made available in a way that is cost-effective, safe, secure, and proliferation-resistant, potentially through a multinational consortium that would provide “cradle-to-grave” nuclear services.

Strengthening safety culture worldwide. Identifying and addressing nuclear facilities with weak nuclear safety culture before this weakness leads to an accident is particularly challenging, as there may be few readily observable signs that safety culture is slipping. Russia and the United States should work with WANO, the IAEA, and other groups to ensure that all countries with nuclear power reactors or other nuclear facilities where an accident could lead to a large-scale release undertake major efforts to strengthen safety culture, including regular training and assessments of progress.

Strengthening and broadening international safety reviews. Reviews by international experts can be particularly effective in identifying safety weaknesses that must be corrected. Today, the IAEA offers several varieties of international safety expert reviews, but these reviews take place only for reactors designated by a country voluntarily requesting a review, and much less than half of the world's reactors have had such an IAEA review. WANO-led peer reviews are closer to being universal – all reactor operators are members of WANO, and in principle committed to accept such peer reviews. Some experts have argued that WANO reviews are not as in-depth or probing as those of some other organizations, such as the U.S. branch of WANO, the Institute of Nuclear Power Operations (INPO). Russia and the United States should work both together and with other countries to strengthen and to broaden international safety reviews, with the goal of ensuring that all nuclear power reactors around the world are subject to effective international reviews every few years. This would potentially be a key tool in finding and fixing the nuclear facilities around the world that pose the highest risks of a major accident.

Achieving Binding Global Nuclear Safety Standards

Russia and the United States, working with other countries, should seek to lead an international negotiation of effective global nuclear safety standards, binding on all participants. As part of such standards, states should commit to accepting IAEA-led peer reviews for major civilian facilities, as discussed above.



Russian and U.S. lab directors meeting at the International Atomic Energy Agency in Vienna in July, 2004. Russia and the United States have the world's largest complexes of nuclear scientists and engineers; expanded cooperation could accelerate progress in nuclear energy, nuclear security, and nonproliferation.
Source: IAEA

Designing the Next Generation of Reactors for High Safety Standards

Russia and the United States, working with other countries, should design future reactors to substantially higher standards of safety even than those achieved by today's facilities. In particular, designs should include as much "passive" safety (which does not rely on power supply or mechanical devices such as pumps) and "inherent" safety (which does not rely on human beings taking correct actions) as possible. Designs should integrate safety and security, benefitting both protection from accidents and protection from sabotage.

Today's nuclear safety requirements were primarily intended for today's reactor designs. New approaches will be required for the future innovative nuclear reactors and nuclear fuel cycle facilities. The IAEA is now working to develop a system of universal requirements which would not be tied to particular reactor types. The goal should be to ensure that as a result of implementation of relevant safety requirements, the radiation risks from all elements of nuclear energy generation, in both normal operation conditions and accident scenarios, would not exceed the economic, health, and environmental risks connected with the operations of other industrial power facilities.

Reducing the size of nuclear power plants can greatly reduce the decay heat that has to be contained in the event of an accident, and the total quantity of radionuclides in the core, greatly simplifying safety design in some cases. As discussed in detail later in this report, small and medium reactors might be built in factories, with a high degree of built-in safety, and greater standardization in construction of each facility than is possible with today's huge reactors, built on the reactor site.

Strengthening Reporting and Other Elements of the Global Safety Regime

Russia and the United States should also work together to strengthen other elements of the global nuclear safety regime, including:

- Strengthened coordination among national regulators, so that once a reactor design is approved in one country, other regulators can use that information and approve the design more rapidly;
- Strengthened international information sharing (through both the IAEA/NEA and WANO systems), including more comprehensive and detailed reporting on safety-related incidents, more in-depth analysis of trends and lessons learned from incidents at similar types of facilities so that each can learn from the others, and more complete implementation of these lessons learned at reactor facilities. A strengthened information sharing system should help identify trends and problems that need to be corrected, and which may be common to reactors in different countries.

3. PREVENTING NUCLEAR TERRORISM

U.S. President Barack Obama and Russian President Dmitri Medvedev have both warned that the possibility that terrorists would get and use a nuclear bomb is a real danger to global security that requires immediate action. Terrorists have also considered sabotage of nuclear power plants. A terrorist sabotage that succeeded in causing a major radioactive release, or worse yet detonation of a terrorist nuclear bomb, would be a catastrophe with far-reaching consequences, and would create public fears that could severely undermine prospects for large-scale nuclear energy growth. Russia and the United States both strongly supported United Nations Security Council Resolution (UNSCR) 1887, which called for a global effort to secure all nuclear stockpiles worldwide within four years, and both countries joined with dozens of others in agreeing on this common objective at the April 2010 nuclear security summit in Washington.

Russia and the United States, who together possess over 95% of the world's nuclear weapons and most of the world's highly enriched uranium (HEU) and separated plutonium, have a special responsibility to lead in securing these stockpiles. Working together, the two countries have already achieved dramatic improvements in protection, control, and accounting for both nuclear weapons and nuclear materials. After the disintegration of the Soviet Union and the transition to a market economy, Russian and U.S. experts worked to implement a radical improvement of systems for nuclear material protection, control, and accounting (MPC&A) at the nuclear facilities of the Russian Federation. Cooperation is continuing, with a focus on exchanging best practices, ensuring that improved systems will be sustained, strengthening regulation, training, and more. Special training centers have been created for both civil and military experts, and thousands of Russian experts have received training in different aspects of MPC&A. But there is more to be done, not only in Russia and the United States, but also around the world.¹⁹

A New Presidential Nuclear Security Initiative

Following on the 2010 nuclear security summit, the United States and Russia should jointly lead a common effort to ensure that all nuclear weapons, separated plutonium, and HEU worldwide is secure and accounted for and that major nuclear facilities are secure from sabotage as well, fulfilling the objectives of the 2010 nuclear security summit. Building on the highly successful nuclear security initiative launched by Presidents Vladimir Putin and George Bush at their Bratislava summit in 2005, the United States and Russia should launch a new Presidential initiative focused on continuing U.S.-Russian cooperation to improve nuclear security in Russia and the United States, and worldwide:

- Within the United States and Russia, this would focus on sustainability, consolidation of nuclear stockpiles to the minimum possible number of locations (including conversion of HEU-fueled research reactors), security culture, regulations, exchanges of best practices, and joint R&D on improved approaches to security, control, and accounting for these stockpiles.
- It would shift from a donor-recipient relationship to a real partnership with ideas, plans, and

¹⁹ For a more detailed discussion, see Matthew Bunn, *Securing the Bomb 2010: Securing All Nuclear Materials in Four Years* (Cambridge, Mass.: Project on Managing the Atom, Harvard University, and Nuclear Threat Initiative, April 2010), http://www.nti.org/e_research/Securing_The_Bomb_2010.pdf (accessed 8 June 2010).

resources contributed by both sides, as envisioned in the early lab-to-lab nuclear material protection, control, and accounting (MPC&A) program.

- Elsewhere, it would involve the United States and Russia cooperating – including with joint teams of experts, in some cases – to help other countries upgrade their nuclear security and accounting systems to meet effective standards.
- It would include an expanded exchange of ideas, best practices, and solutions to common problems among those implementing nuclear security in Russia, the United States, and other countries.
- It would include the United States and Russia working to ensure that all countries with nuclear weapons, HEU, separated plutonium, or major nuclear facilities potentially vulnerable to sabotage have effective security regulations in place and adequately enforced.
- This initiative should include a major new effort to ensure reactors worldwide are secure against sabotage, including designing and implementing effective physical protection systems for existing reactors (including armed guards, still not present at facilities in some countries), and designing new reactors with improvements in inherent security built-in from the beginning.

Effective Global Nuclear Security Standards and Agreements

The United States and Russia should also work together, in cooperation with other leading nuclear states, to forge effective global standards for nuclear security, building on agreements already in place, such as the amended Convention on Physical Protection of Nuclear Materials and Facilities, the International Convention on the Suppression of Nuclear Terrorism, the IAEA's physical protection recommendations, and more.

In particular, UNSC Resolution 1540 already legally requires all member states to provide “appropriate effective” security and accounting for any nuclear weapons and related materials they may have. If the plain language of “effective” means anything, it means that these nuclear security systems must be effective in protecting against the kinds of threats terrorists and criminals have shown they can pose. Russia and the United States should lead a global cooperative effort to ensure that all countries with HEU and plutonium provide effective security for these stocks:

- Even in the safest countries, all nuclear weapons and Category I nuclear materials must be protected against a range of possible types of adversary theft attempts, including *at least* against two small teams of well-armed, well-trained outsiders, plus one insider;
- Countries facing higher threats (e.g., Pakistan) should protect nuclear weapons and materials against more capable adversaries;
- Participants in cooperative nuclear security efforts should work out means – consistent with necessary secrecy – to build confidence that each participant has an effective nuclear security system in place.²⁰

At the same time, Russia and the United States should work together to strengthen existing

20 For further discussion, see Matthew Bunn and Col.-Gen. Evgeniy P. Maslin, “All Stocks of Weapons-Usable Nuclear Materials Worldwide Must be Protected Against Global Terrorist Threats,” presented to the WINS Workshop on “Protecting Nuclear Programmes From International Terrorism,” 19-20 November 2009, <http://belfercenter.ksg.harvard.edu/files/all-stocks-of-weapons-usable-material-eng.pdf> (accessed 4 June 2010).

instruments of the nuclear security regime, including: completing the latest revision of the IAEA's physical protection regulations and ensuring that states around the world implement the measures called for as rapidly as possible; convincing all states with significant nuclear activities to ratify the Convention on Physical Protection and the 2005 amendment that extends its coverage to nuclear materials in domestic use and storage and to sabotage; convincing all states to ratify the International Convention on the Suppression of Acts of Nuclear Terrorism, first proposed by Russia; and strengthening the physical protection requirements the members of the Nuclear Suppliers Group insist on as a condition of nuclear exports.

Consolidating and Reducing Stockpiles

Russia and the United States should cooperate to reduce the number of buildings and sites with warheads and fissile materials to the absolute minimum required, providing higher security at lower cost. Russia and the United States should each develop a strategic plan for consolidating their nuclear weapons and weapons-usable nuclear materials to the maximum extent possible, assessing each building where these items exist, its continuing missions, their benefits, costs, and risks, and whether there are ways to accomplish those missions without the use of HEU or plutonium. As part of this effort, Russia and the United States should cooperate to convert research reactors from HEU to LEU and to shut down research reactors whose continuing missions no longer justify their costs and risks. This effort should include both (a) sites within Russia and the United States and (b) helping other countries to do the same. As Russian President Medvedev and U.S. President Obama have agreed, the goal should be to minimize the civil use of HEU to the maximum extent feasible;²¹ indeed, with the development of new fuels for research reactors and new approaches to producing isotopes, it may be possible to eliminate the civil use of HEU entirely. Neither the United States nor Russia has produced additional HEU for many years, and given the huge stockpiles that exist, there will be no need for further production of HEU for either civil or military purposes, at least for many decades to come; Russia and the United States should seek an agreement to end production of HEU for any purpose.

All countries where HEU or separated plutonium are present should adopt regulations that require higher security for these materials than for LEU; such regulations will provide appropriate security for the most dangerous materials, and the higher cost of providing security for HEU or separated plutonium will encourage facilities to eliminate these materials wherever possible.

Russia and the United States must also act to address the huge stockpiles of nuclear weapons, plutonium, and HEU built up over the decades of the Cold War. The first priority, of course, is that all of these stockpiles should be maintained under the highest practicable standards of security and accounting. Then, as described in the next chapter, Russia and the United States should work to reach agreement on deep, transparent, and irreversible reductions in their nuclear stockpiles.²² They should reduce their nuclear weapon stockpiles to the minimum required for their national security needs; verifiably dismantle all the nuclear weapons beyond the low agreed remaining stocks; place the resulting plutonium and HEU in secure, monitored storage; and ultimately eliminate these excess stocks of plutonium and HEU.

21 "Joint Statement by President Barack Obama of the United States and President Dmitry Medvedev of the Russian Federation on Nuclear Cooperation," 6 July 2009.

22 For a seminal early discussion, see Evgeniy P. Velikhov and John P. Holdren, co-chairs, *U.S.-Russian Independent Scientific Commission on Disposition of Excess Weapons Plutonium: Final Report* (Washington, D.C.: Office of Science and Technology Policy, June 1, 1997). For a more recent account, see Matthew Bunn and Anatoli Diakov, "Disposition of Excess Highly Enriched Uranium," and "Disposition of Excess Plutonium," in *Global Fissile Materials Report 2007* (Princeton, NJ: International Panel on Fissile Materials, October 2007), pp. 24-32 and 33-42.

The current U.S.-Russian HEU Purchase Agreement is one of the most successful examples of U.S.-Russian nonproliferation cooperation. Under this deal, over 380 tons of weapons-grade HEU, enough for over 15,000 nuclear weapons, has been permanently destroyed, providing billions of dollars in revenue to the Russian nuclear industry and a reliable low-cost supply of fuel to the U.S. nuclear industry. Indeed, it is a remarkable fact that nearly one out of every ten light bulbs in the United States is powered with fuel from a dismantled nuclear weapon once targeted on the United States. The current purchase agreement will expire in 2013, after the blending down of 500 tons of HEU. If public estimates are correct, at that time Russia will still have hundreds of tons of HEU not needed for its military programs (though some of this material may be less than weapon-grade, or contaminated in a variety of ways). While Russia has made clear that the specific structures of the existing agreement are not profitable enough to be renewed, there are a variety of other possible blend-down approaches that could earn Russia billions of dollars in additional revenue and provide a guaranteed fuel supply to support both Russia's domestic nuclear energy plans and its hopes for nuclear exports.²³ The United States, too, should declare substantial additional quantities of HEU to be excess to its military needs and blend them down to LEU for civilian use. Russia and the United States, for example, could increase public enthusiasm for nuclear energy by linking it to disarmament, promising to provide fuel blended from HEU for the first few years of operation for each new reactor purchased from their nuclear companies.



Upgraded fencing and intrusion detectors at a nuclear site in Russia. U.S.-Russian cooperation has led to major improvements in security for nuclear weapons and materials, greatly reducing risks to the security of Russia, the United States, and the world.

Source: U.S. Department of Defense

Excess plutonium poses more difficult challenges, as it cannot readily be blended with other isotopes to prevent its use in weapons, and any disposition option is likely to be costly. Russia and the United States should follow through on the plutonium disposition protocol signed in April 2010, and, as additional arms reductions mean that more material is no longer needed for military purposes, they should each declare large quantities of additional plutonium as excess to their military needs and subject to disposition.²⁴ They should maintain the highest practicable standards of security and accounting throughout the processes of plutonium and HEU disposition, to ensure that these efforts reduce, rather than increasing, the dangers posed by these massive excess stockpiles.

Of course, as we reduce stockpiles of fissile materials, it is important not to build up more at the same time. Both Russia and the United States stopped producing plutonium or HEU for nuclear weapons decades ago, and have pledged not to resume. The last Russian plutonium production reactor, at Zheleznogorsk, recently shut down, representing another success for U.S.-Russian

23 See, for example, Matthew Bunn, "Expanded and Accelerated HEU Downblending: Designing Options to Serve the Interests of All Parties," in *Proceedings of the Institute for Nuclear Materials Management 49th Annual Meeting*, Nashville, Tenn., 14-17 July 2008 (Deerfield, IL: INMM, 2008).

24 See Bunn and Diakov, "Disposition of Excess Plutonium."

nonproliferation cooperation. While production of fissile materials for weapons only continues in a few countries, weapons-usable plutonium continues to build up in civilian stockpiles, with the result that today, there are some 250 tons of weapons-usable plutonium in civilian stocks, as much or more as is in all the world's weapon stockpiles combined. Whether countries plan on an open or a closed fuel cycle, it should be possible to agree that spent fuel should not be reprocessed until the plutonium it contains is needed as fuel. Russia and the United States should work together to attempt to overcome the current obstacles to a verified global agreement to end further production of fissile materials for weapons, and to reduce the accumulation of fissile materials in civilian stockpiles.

Security Culture

Russia and the United States should each undertake major efforts to strengthen security culture throughout their nuclear complexes, ensuring that all staff understand the threat of nuclear terrorism and give nuclear security high priority. Every facility or transporter managing nuclear weapons, HEU, plutonium, or facilities and transports whose sabotage could cause catastrophic consequences should have a targeted program to strengthen security culture. This effort should include regular training, incentives for contributing to stronger security, and regular assessments of progress in strengthening security culture.

Russia and the United States should lead a substantial effort to convince other countries to take similar measures around the world. In particular, the Russian and U.S. governments should work closely with the nuclear industry to instill a philosophy of continuous improvement and a never-ending quest for excellence in nuclear security, as many firms have adopted in the case of nuclear safety.

Expanded International Nuclear Security Cooperation

Seizing the initiative from the 2010 nuclear security summit, Russia and the United States should work together to expand and to accelerate international cooperation focused on strengthening nuclear security and stopping nuclear smuggling, to meet the agreed goal of securing all vulnerable weapons-usable nuclear material worldwide within four years. They should work to ensure that every country with weapons-usable nuclear material is participating in the effort, along with potential transit states and countries with expertise and resources to contribute. They should work to ensure that this effort has adequate resources and strong frameworks for cooperation.

Resources: Extending the Global Partnership

As President Obama has proposed, Russia and the United States, with other members of the Group of Eight industrialized democracies and the other contributors to the Global Partnership Against the Spread of Weapons and Materials of Mass Destruction, should agree to extend the Global Partnership for another 10 years and to provide an additional \$10 billion over that period. They should agree to expand the partnership's mission to helping countries all over the world put in place effective security and other controls for nuclear, chemical, and biological weapons and materials, to meet their obligations under UNSCR 1540.

Frameworks for Cooperation

Expanding the IAEA's Role. Russia and the United States should work with other members of the IAEA Board of Governors to strengthen the IAEA's important role in nuclear security. This should include expanding the budget of the Office of Nuclear Security and incorporating it in the IAEA's regular budget; establishing a risk-based priority assessment process for the office; an expanded role for the IAEA in helping states meet their UNSCR 1540 nuclear security and accounting obligations; larger-scale use of IAEA-led international peer reviews of nuclear security; a continuing effort to develop and strengthen IAEA nuclear security recommendations and guides; and clear instruction (and training) so that when safeguards inspectors notice nuclear security problems, these are appropriately reported. Ultimately, states should negotiate binding agreements setting effective nuclear security standards, and give the IAEA an important role in confirming that states are living up to their nuclear security commitments.

Strengthening the Global Initiative to Combat Nuclear Terrorism. Russia and the United States should work together, and with other participants, to strengthen the Global Initiative (GI) while preserving its flexibility. The Global Initiative can focus more on exchanging nuclear security best practices, helping to arrange cooperation to upgrade security at particular sites, making efforts to strengthen nuclear security regulations, promoting nuclear security culture, and more. At the same time, it should focus additional attention on organizing realistic exercises and simulations that help highlight the dangers of nuclear terrorism for policymakers and nuclear facility managers.

Following up the nuclear security summit. Russia and the United States should work together to ensure that the follow-up to the 2010 nuclear security summit and the preparations for the 2012 nuclear security summit in South Korea becomes a practical, action-oriented process focused on ensuring that the pledges from the nuclear security summit are transformed into actions on the ground – and extended where necessary. They should seek to ensure that each participating country designates a senior official to participate in the follow-up meetings who is able to draw on the full resources of his or her government, rather than representing only a single agency, and they should seek to ensure that these officials meet regularly to map out plans for the actions needed to meet the agreed objective of securing all nuclear material worldwide in four years. Russia and the United States should work together to develop clear indicators to assess progress in improving nuclear security, along with measures by which, within the constraints of necessary secrecy, states can provide enough information to other states to build confidence that they are in fact implementing their nuclear security commitments.

Deterring Nuclear Theft, Smuggling, and Sabotage

Russia and the United States should work with countries all around the world to ensure that each country puts in place criminal laws imposing severe penalties for crimes related to theft and smuggling of nuclear materials or sabotage of nuclear facilities – including *attempts* to commit these crimes and *assistance* to others in committing such crimes. Russia and the United States should also lead an effort to ensure all key countries have units of their national police trained and equipped to deal with nuclear cases. Russia and the United States should expand coopera-

tion between their police and intelligence agencies focused on stopping nuclear smuggling and identifying and countering terrorist groups interested in nuclear weapons, and encourage other countries to take part as well.

Nuclear forensics can play an important role in the effort to stop nuclear smuggling, by helping to identify possible sources for nuclear material, or ruling out others. Russian and U.S. labs have advanced capabilities in nuclear forensics, but there is much still to be done to improve international capabilities in this area. Russia and the United States should direct their leading labs to establish in-depth cooperation to improve nuclear forensics capabilities. Each country should also establish a database of its own nuclear material, against which seized material might be compared. Russian and U.S. scientists should cooperate to develop means by which such data could be exchanged without compromising necessary secrecy.

4. PREVENTING NUCLEAR PROLIFERATION

The global effort to stem the spread of nuclear weapons has been highly successful, but is now under immense stress:²⁵

- North Korea has become the first country ever to withdraw from the Nonproliferation Treaty (NPT) and test a nuclear weapon.
- The International Atomic Energy Agency (IAEA) has reported: that Iran has committed numerous “breaches of its obligation to comply” with its safeguards agreement; that Iran is continuing to develop its enrichment program in defiance of legally binding UN Security Council resolutions requiring it to suspend enrichment and reprocessing; that the IAEA is in possession of “extensive” and “broadly consistent and credible” evidence which “raises concerns about the possible existence in Iran of past or current undisclosed activities related to the development of a nuclear payload for a missile”; and that Iran “has not provided the cooperation necessary” for the IAEA to confirm that all of its nuclear material is in peaceful activities.²⁶
- The United States has released extensive intelligence information suggesting that the facility in Syria that was bombed by Israel in September 2007 was a covert nuclear reactor being built with North Korean help.²⁷ Although Syria leveled the site after the 2007 attack, the IAEA has concluded that the site’s features are “similar to what may be found at nuclear reactor sites,” has found chemically processed uranium particles at the site which do not appear to be consistent with having come from the Israeli attack, and has found traces at other sites that have led Syria to acknowledge previously unreported nuclear material. Since 2008, Syria has refused IAEA requests to revisit the site or to visit three other sites the IAEA believes are related.²⁸
- A global black-market network led by Pakistan’s A.Q. Khan marketed centrifuge technology and, in some cases, nuclear weapons designs to countries such as Libya, Iran, and North Korea – and black market nuclear technology purchase attempts continue.
- Some terrorist groups, including al Qaeda, are actively seeking nuclear weapons.
- The U.S.-led invasion of Iraq in 2003, not authorized by the United Nations, provoked a sharp international reaction and undermined the credibility of U.S. intelligence judgments when no nuclear, chemical, or biological weapons were found there. It may also have strengthened the arguments of those in North Korea and Iran who believe their countries need nuclear deterrents.

25 See, for example, Commission of Eminent Persons, *Reinforcing the Global Nuclear Order for Peace and Prosperity: The Role of the IAEA to 2020 and Beyond* (Vienna: International Atomic Energy Agency, May 2008), <http://www.iaea.org/NewsCenter/News/PDF/2020report0508.pdf> (accessed 8 June 2010). The suggestions in this report draw heavily on that document.

26 The IAEA first reported in detail on breaches of Iran’s safeguards agreement in IAEA, *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2003/75 (Vienna: IAEA, 10 November 2003). The other quotes here are from IAEA, *Implementation of the NPT Safeguards Agreement and Relevant Provisions of Security Council Resolutions 1737 (2006), 1747 (2007), 1803 (2008), and 1835 (2008) in the Islamic Republic of Iran*, GOV/2010/10 (Vienna: IAEA, 18 February 2010).

27 See Office of the Director of National Intelligence, “Background Briefing with Senior U.S. Officials on Syria’s Covert Nuclear Reactor and North Korea’s Involvement” (Washington, D.C.: ODNI, 24 April 2008), http://dni.gov/interviews/20080424_interview.pdf (accessed 30 July 2010). The video that accompanied this briefing is available at <http://www.reuters.com/news/video?videoId=81150> (accessed 30 July 2010).

28 IAEA, *Implementation of the NPT Safeguards Agreement in the Syrian Arab Republic*, GOV/2010/29 (Vienna: IAEA, 31 May 2010).

- The inexorable spread of technology and the revival of interest in nuclear power are contributing to fears that sensitive technologies that could be used to make nuclear weapons may become available to more and more countries.
- The U.S.-India nuclear deal, later approved by the Nuclear Suppliers Group, gave India access to the same nuclear cooperation that non-nuclear-weapon states that are party to the NPT receive, without India accepting safeguards on all its nuclear activities, or giving up or even capping its nuclear weapons. Coming less than a decade after India's 1998 nuclear tests, this strengthened the arguments of nuclear weapons advocates in other countries, who argue that international condemnation of their nuclear programs will be brief and ineffectual.
- Sharp disagreements over whether the nuclear weapon states are fulfilling their obligation to negotiate in good faith toward nuclear disarmament have slowed progress in gaining agreement on new steps to strengthen the NPT regime, and contributed to the collapse of the 2005 NPT Review Conference. Those disagreements remain, despite the success in reaching a broad consensus document at the May 2010 NPT Review.

Even if nuclear power was not likely to grow, substantial actions would be needed to strengthen the global effort to stem the spread of nuclear weapons, in the interests of all. But even more substantial actions will be needed to prevent proliferation in a world in which nuclear energy grows and is made more broadly available around the world. Widespread proliferation would undermine public support for nuclear energy. Hence, limiting proliferation is important to achieving large-scale nuclear energy growth.

One of the main conclusions of the IAEA's "International Nuclear Fuel Cycle Evaluation" in the late 1970s was that nonproliferation could not be resolved through technical means alone, no matter what fuel cycle choices countries made; minimizing the risk – which can never be reduced to zero – requires a combination of political, organizational, and technical measures. This conclusion is still valid today.

Russia and the United States should lead a sustained global effort to:²⁹

- Engage the hard cases with direct diplomatic engagement and international packages of incentives and disincentives large enough and credible enough to convince them that it is in their interests to verifiably give up their nuclear weapons ambitions;
- Strengthen nuclear safeguards;
- Take new steps to stop black-market networks;
- Stem the spread of enrichment and reprocessing;

29 For compilations of recommended steps to strengthen the nuclear nonproliferation regime, see, for example, Commission of Eminent Persons, *Reinforcing the Global Nuclear Order for Peace and Prosperity*; George Perkovich et al., *Universal Compliance: A Strategy for Nuclear Security* (Washington, D.C.: Carnegie Endowment for International Peace, 2005, updated 2007), http://www.carnegieendowment.org/files/univ_comp_rpt07_final1.pdf (accessed 7 June 2010); Weapons of Mass Destruction Commission, Hans Blix, chairman, *Weapons of Terror: Freeing the World of Nuclear, Biological, and Chemical Arms* (Stockholm: Weapons of Mass Destruction Commission, 2006), http://wmdcommission.org/files/Weapons_of_Terror.pdf (accessed 7 June 2010); and International Commission on Nuclear Non-Proliferation and Disarmament, Gareth Evans and Yoriko Kawaguchi, co-chairs, *Eliminating Nuclear Threats: A Practical Agenda for Global Policymakers* (Canberra/Tokyo: International Commission on Nuclear Non-Proliferation and Disarmament, November 2009), http://www.icnnd.org/reference/reports/ent/pdf/ICNND_Report-EliminatingNuclearThreats.pdf (accessed 7 June 2010).

- Toughen enforcement;
- Reduce demand for nuclear weapons; and
- Keep the nuclear weapons' states end of the nonproliferation bargain by bringing the Comprehensive Test Ban (CTB) into force, achieving deep reductions in nuclear weapons, negotiating a fissile cutoff, transparently reducing excess HEU and plutonium stockpiles, offering negative security assurances, and more.

The UN Security Council unanimously endorsed a broad range of initiatives in these directions in Resolution 1887, which both Russia and the United States supported.³⁰ And the May 2010 NPT Review Conference, representing the vast majority of the world's countries, reached consensus on a final document that included action plans to strengthen each of the three pillars of the NPT – nonproliferation, disarmament, and peaceful uses of nuclear energy.³¹ Building on that effort, Russia and the United States should create a joint committee to develop proposals for strengthening the nonproliferation regime. Even before such a committee begins its work, however, several important steps can be identified, which are discussed below. Strengthening the barriers that prevent nuclear energy from contributing to the spread of nuclear weapons is important to the future of nuclear energy, and should be a central element of U.S.-Russian nuclear energy cooperation.

Reducing Proliferation Dangers in Iran and North Korea

To have any substantial chance of resolving the challenges to the nonproliferation regime posed by Iran and North Korea will require close cooperation between Russia, the United States, and other countries.

North Korea

North Korea has withdrawn from the NPT, expelled inspectors, and tested nuclear weapons. It has sold missiles to many states, and if U.S. charges are correct, it also helped Syria construct a covert plutonium production reactor. Given the nature of the North Korean regime, achieving lasting, verifiable agreements to cap the North Korean arsenal, to prevent any further transfers of nuclear technology or materials, and ultimately eliminate North Korea's nuclear weapons will be an immense challenge – but a crucial one for the future of international security.

Russia and the United States have both been key participants in the six-party talks with North Korea, and both share strong national interests in seeing a non-nuclear Korean peninsula and in avoiding any further nuclear transfers from the North. Both have key roles to play: the United States is the country North Korea most fears, and credible U.S. assurances and incentives could be powerful tools for resolving the crisis. Russia, for its part, is less feared by North Korea and may be able to help, along with key players such as China, in bridging gaps to resolve the key issues.

Despite recent North Korean behavior, it is important to convince North Korea to restart

30 *United Nations Security Council Resolution 1887, S/RES/1887* (2009) (New York: United Nations, 24 September 2009), [http://daccess-ods.un.org/access.nsf/Get?Open&DS=S/RES/1887%20\(2009\)&Lang=E&Area=UNDOC](http://daccess-ods.un.org/access.nsf/Get?Open&DS=S/RES/1887%20(2009)&Lang=E&Area=UNDOC) (accessed 11 June 2010).

31 *2010 Review Conference of the Parties to the Treaty on the Non-Proliferation of Nuclear Weapons: Final Document, NPT/Conf.2010/50* (New York: United Nations, May 2010), <http://www.reachingcriticalwill.org/legal/npt/revcon2010/FinalDocument.pdf> (accessed 11 June 2010).

serious discussions in both bilateral and six-party formats. A step-by-step approach based on the “action for action, words for words” formula that has succeeded in these talks in the past is likely to be essential. Russia and the United States must work with other countries to structure an internationally agreed package of carrots and sticks that can ultimately convince North Korea that it is in its national interests to cap and then dismantle its nuclear weapons capabilities, as called for in the agreed statement of 2005.

To help prevent North Korean nuclear transfers, Russia and the United States should (a) cooperate to ensure that Russia’s limited border with North Korea is tightly controlled, and that effective radiation detectors are available there; (b) work with China to strengthen controls along its border with North Korea; (c) work together and with regional countries to enforce UN resolutions prohibiting a range of North Korean nuclear transfers; and (d) exchange any data they may have concerning North Korean plutonium and uranium, to increase the chances that if any nuclear material from North Korea were seized, it could be traced back to its source.

Iran

Iran also poses major challenges to the global nonproliferation regime, though it remains a part to the NPT and all of its declared nuclear facilities are under international inspection. But Iran has a growing enrichment capability, which could be adapted quickly to produce highly enriched uranium for nuclear weapons. The IAEA has reported important evidence that raises concern over possible Iranian work on a nuclear weapon design. Iran has extensively violated its safeguards agreement with the IAEA and has refused to comply with legally binding UN Security Council resolutions requiring it to suspend enrichment and reprocessing activities and to provide broad transparency.

Russia and the United States have different relationships with Iran. The United States and Iran have a record of decades of enmity and mistrust, making discussions and negotiations difficult, and have not had diplomatic relations since the founding of the Islamic Republic in 1979. Russia and Iran, by contrast, have diplomatic relations and substantial trade and cooperation in a variety of areas.

Russia and the United States are both key participants in the P5+1 group that has been working together to address the Iranian nuclear challenge. Russia has supported a series of UN resolutions requiring Iran to take steps to build international confidence in the peaceful nature of its nuclear program and imposing sanctions when it refused to comply. Russia has committed not to provide any technology to Iran that would contribute to a nuclear weapons program, and has stopped a number of transfers of potentially sensitive technology to Iran that were not authorized by the Russian government. The United States and Russia have disagreed about Russia’s decision to provide a safeguarded light-water reactor (LWR) to Iran – the VVER-1000 nearing completion at Bushehr. But the P5+1, including the United States, have supported Iran’s right to the use of nuclear energy, when in compliance with its NPT obligations, and the United States has supported Russia’s action in negotiating a fuel agreement requiring Iran to return all of the plutonium-bearing spent fuel from Bushehr to Russia.

Russia and the United States should strengthen their cooperation within the P5+1 to launch a genuine engagement with the Iranian government designed to reduce the risks to international

security posed by Iran's nuclear program, and to keep Iran from moving to produce nuclear weapons. If the P5+1 want Iran to address their concerns, it is clear that they will have to address some of Iran's concerns as well; as with North Korea, a step-by-step approach is likely to be needed, with an international package of incentives and disincentives big enough and credible enough to convince the Iranian government that it is in its national interests to abandon its nuclear weapons efforts.

There are several specific cooperative steps Russia and the United States should take. First, there is the issue of Iran's low-enriched uranium (LEU) stockpile. This LEU is important because, with a given amount of enrichment capacity, Iran could produce HEU for a weapon roughly four times faster if it was enriching from LEU than if it was enriching from natural uranium. This is why the P5+1 sought Iran's agreement to export 1200 kilograms of LEU in the fall of 2009. Unfortunately, Iran did not live up to its initial agreement to this approach, and then agreed to export the same amount in a 2010 pact with Brazil and Turkey, once it had produced enough additional LEU that exporting 1200 kilograms still left Iran with enough LEU to rapidly enrich into material for a nuclear weapon, should it so choose. Moreover, Iran used the failure of the negotiations over this fuel swap as an excuse to begin enriching uranium to 20% U-235. But there are still options to accomplish the original P5+1 goals. Russia, the United States, and the rest of the P5+1 should follow up Iran's recent agreement with Brazil and Turkey by seeking Iran's agreement to transform that initial fuel swap into an ongoing fuel swap, in which Iran would send LEU to Russia as it was produced, reducing the amount of LEU in Iran to far below the amount needed to produce enough HEU for a nuclear weapon and maintaining the stock at that low level, while Russia would provide fabricated fuel for the Bushehr reactor in return. They should also seek Iran's agreement, as part of this arrangement, not to enrich uranium to more than 5% U-235. This would fulfill what Iran has always said is the purpose of its enrichment program – providing civilian reactor fuel.

Russia and the United States should also work together to eliminate the HEU research-reactor fuel that currently exists in Iran. There are several kilograms of U.S.-supplied irradiated HEU fuel at the Tehran research reactor, left over from the Shah's time. There is little political prospect that Iran and the United States will agree that this will be shipped to the United States; but given ongoing Russian-Iranian cooperation, it might well be possible for Russia to convince Iran to ship it to Russia. Since this is spent fuel, it should in principle be of little value to Iran, but it still includes several kilograms of fairly highly enriched material, and the radioactivity of this fuel has been cooling for decades, so it does pose some proliferation risk. Since this fuel is U.S.-origin, it cannot legally be shipped to Russia until a U.S.-Russian agreement on civilian nuclear energy cooperation has entered into force.

Strengthening Safeguards

The IAEA's safeguards system is central to preventing the spread of nuclear weapons and enabling civilian commerce in nuclear energy. Russia and the United States have vital national interests in strengthening the IAEA and in ensuring that it has the authority, resources, personnel, and technology needed to do its job. As nuclear energy grows and spreads, there will be increasing demands on the IAEA. Several of the participants in this study also participated in the Commission of Eminent Persons, which provided a sweeping set of recommendations to build a

stronger global nuclear order and a stronger IAEA. We believe those recommendations should be implemented.³²

In particular, Russia and the United States should:

- Work with other states to gain approval for increasing the IAEA's budget and, in the meantime, expand their voluntary contributions to the IAEA.
- Assist the IAEA with state-of-the-art technology to support its safeguards missions.
- Provide the IAEA with high-quality intelligence relevant to its safeguards missions.
- Recruit skilled experts from their laboratories and industry to serve on the IAEA staff.
- Continue to support the Additional Protocol as the new standard for international safeguards, and in particular to make acceptance of the Additional Protocol a condition for new nuclear exports.
- Support the IAEA's efforts to strengthen its approach to safeguards, including the state-based information-driven approach, the unit monitoring illicit nuclear transfers, and the IAEA's efforts to clarify weaponization issues when they arise.
- Undertake R&D programs (both separate U.S. and Russian programs and joint efforts) to develop improved safeguards technologies to address key IAEA needs.
- Support placing all of their enrichment and reprocessing activities under international monitoring as part of the negotiation of a fissile cutoff treaty – and as part of moving to a world of greater international control over sensitive elements of the nuclear fuel cycle everywhere. Russia is taking steps to ensure that the IAEA will be able to apply safeguards at the Angarsk enrichment plant, as part of the effort to establish an international enrichment center there, described below. The United States should make all the new enrichment plants it is planning eligible for IAEA safeguards, and should provide the IAEA with the resources required to actually implement such safeguards.

Stopping Black-Market Nuclear Networks

Controlling the technologies that can be used for nuclear weapons programs is fundamental to the goal of expanding nuclear energy without increasing proliferation risks. The fact that the global black-market nuclear network led by A.Q. Khan operated in some 20 countries for decades before it was shut down makes clear that additional steps are needed to control sensitive nuclear and dual-use technologies.³³

UN Security Council Resolution (UNSCR) 1540 creates a binding legal obligation on all UN member states to provide “appropriate effective export controls, border controls, and transshipment controls.” While “appropriate effective” is not defined, it seems clear that to be considered appropriate and effective, a system would need to be able to reliably detect, stop, and appropri-

32 Commission of Eminent Persons, *Reinforcing the Global Nuclear Order for Peace and Prosperity*.

33 For detailed accounts of this episode, with recommendations for preventing such networks in the future, see, for example, International Institute for Strategic Studies, *Nuclear Black Markets: Pakistan, A.Q. Khan and the Rise of Proliferation Networks: A Net Assessment* (London: IISS, 2007), and David Albright, *Peddling Peril: How the Secret Nuclear Trade Arms America's Enemies* (New York: Free Press, 2010).

ately punish illicit exports.

Russia has greatly strengthened its controls over exports of dangerous technologies since the 1990s, and the United States is in the process of reforming its export control system. But as with nuclear security, staying ahead of adversaries who are continually seeking ways to overcome existing controls requires a never-ending effort to improve control systems.

At the same time, the effort to cope with black-market nuclear networks must go far beyond export controls, to include international police and intelligence cooperation, establishing and enforcing effective criminal penalties for illicit exports, combating corruption in the nuclear sector and among export control and border control officials, and more.

Russia and the United States should work together to:

- Strengthen the effectiveness of their national export control systems, exchanging best practices, developing partnerships with industry, ensuring that those controlling exports are fully informed about illicit trafficking threats (including relevant firms, front companies, patterns of acquisition, technologies being sought, and the like), and updating control lists to keep pace with changing technology.
- Expand assistance efforts to help countries worldwide implement their obligations under UNSCR 1540, potentially including drafting model legislation.
- Work with industry to ensure that firms with access to sensitive nuclear and dual-use technologies understand the rules and have effective internal processes to identify and deal with suspect inquiries.
- Expand cooperation among Russian and U.S. police, export control, and intelligence agencies, and those of other countries, focused on finding and disrupting black market nuclear networks.
- Support and provide information to the IAEA's effort to track black-market nuclear networks, advocating for more resources and priority; additional personnel; and an expanded mission for this effort, not simply providing information in support of safeguards but also helping states to shut down these networks and find and fix leaks in their control systems.
- Provide the IAEA with information not only on exports and imports of listed nuclear and dual-use technologies, but on export denials and inquiries as well, and encourage other states to do the same.
- Share with each other, and with other countries, information on the nuclear-related shopping activities of countries suspected of seeking nuclear weapons, along with watch lists identifying particular firms, front companies, and organizations believed to be involved in illicit nuclear trade.
- Work with other countries to interdict financing for illicit nuclear transactions, following the model of international cooperation focused on blocking terrorist financing.
- Work with other countries to continue to strengthen the Global Partnership Against the Spread of Weapons and Materials of Mass Destruction, the Proliferation Security Initiative, and the Global Initiative to Combat Nuclear Terrorism.

Civilian Employment for Former Weapons Scientists

Scientists working together have taken the lead in many aspects of U.S.-Russian cooperation. After the collapse of the Soviet Union, there was a particular concern about the potential proliferation risks posed by underemployed experts in weapons technologies. This led to the establishment of cooperative programs such as the International Science and Technology Centers (ISTC), the Initiatives for Proliferation Prevention (IPP) program (later renamed), the Civilian Research and Development Foundation (CRDF), and more.

Experts who once worked on weapons also represented – and still represent – an immense resource of scientific and technological talent, with the potential for a wide range of contributions, particularly in nuclear energy.

With the stabilization and growth of Russia's economy, the lessons of the A.Q. Khan network, and the new realization of the importance of potential terrorist threats, the proliferation risks these programs were once designed to address have changed profoundly. There remains, however, a need for programs targeted on making use of the immense talents of former weapons experts around the world for civilian needs. Russia and the United States should jointly review how best to enable and incentivize civilian contributions from these high-technology experts, and modify their national and joint efforts appropriately. In particular, they should create mechanisms to support all scientists with relevant expertise – whether former weapon scientists or not – to work together to develop new technologies for nuclear energy, nuclear security, and nuclear verification.

Limiting the Spread of Enrichment and Reprocessing Facilities

Limiting the spread of enrichment and reprocessing technologies is particularly important, as these are the technologies that make it possible to produce nuclear material for nuclear weapons. Some countries, understanding that they have no need for such risky technologies, may be willing to sign agreements requiring them not to establish such facilities, as the United Arab Emirates (UAE) did in its nuclear cooperation agreement with the United States.³⁴ But many countries are likely to be reluctant to foreclose their right to implement such technologies in the future. Hence, it is important to focus on structuring incentives that convince states that there is no need to implement those rights by investing the enormous resources required to build their own enrichment and reprocessing plants.

This is where new institutional arrangements such as Russia's International Uranium Enrichment Center (IUEC) at Angarsk and concepts such as an IAEA-controlled fuel bank can play an important role. The IUEC gives any country that wishes to participate access to enriched fuel guaranteed by a binding government-to-government agreement, and a share in the profits the center generates, without providing any access to sensitive enrichment technology.³⁵ The IUEC appears already to have had some success in limiting incentives for the spread of enrichment, as

³⁴ *Agreement for Cooperation Between the Government of the United States of America and the Government of the United Arab Emirates Concerning Peaceful Uses of Nuclear Energy* (Washington, D.C.: U.S. Department of State, 21 May 2009).

³⁵ The Angarsk enrichment plant continues to be owned and operated entirely by Russia, with staff who are Russian citizens with Russian security clearances as needed; the IUEC is a legal entity which contracts with the Angarsk plant for enrichment services.

Kazakhstan had previously expressed an interest in uranium enrichment in order to capture more of the value-added from its uranium resources, but has indicated that for now, their participation in the IUEC is sufficient to meet that objective. Moreover, Russia has negotiated arrangements with the IAEA, approved by the IAEA Board of Governors in late 2009, for LEU controlled by the IUEC to serve as the first element of a system of fuel reserves the IAEA could draw on: under these arrangements, if any country that is complying with its NPT and safeguards obligations is ever cut off from its fuel supply by a political disagreement with a supplier, that country could appeal to the IAEA, which

would, if the state met its criteria, draw on the fuel at the IUEC to provide an alternative supply. The United States is establishing a similar reserve, made from blending excess HEU to LEU. But some countries may see reserves on the territories of the same suppliers that were already supplying their fuel as offering only modest additional assurance of supply; hence, as a final backup, the IAEA is working to establish an IAEA-controlled fuel reserve, financed with contributions from the non-profit Nuclear Threat Initiative (NTI) and several countries. Such concepts could provide an important backup to existing market arrangements (which already provide highly reliable fuel supplies for most countries), thereby reducing states' incentives to build their own enrichment plants. These initiatives should not be seen as in any way restricting states' rights to nuclear energy under Article IV of the NPT; indeed, they offer *more* than states have ever had available to them before under Article IV, a guarantee of reliable fuel supplies for as many reactors as states decide to build.

At the same time, Russia and the United States should continue to expand their joint efforts to reach agreement in the Nuclear Suppliers Group (NSG) on strengthening the NSG guidelines on export of enrichment and reprocessing technology; they should cooperate (as discussed below) to address the most difficult current cases of the spread of enrichment and reprocessing technology; they should continue to work with other major nuclear fuel suppliers to develop common approaches to nonproliferation and fuel supply questions (including further development of attractive package offers that might be made to encourage countries not to bother investing in their own enrichment and reprocessing facilities); and they should expand their cooperation, working with other countries, focused on stopping black-market networks in enrichment and reprocessing technologies, including expanding cooperation between governments and private firms, between international police, customs, and intelligence agencies, and with the IAEA.



Uranium processing equipment at the Angarsk enrichment plant in Russia. Russia has launched the International Uranium Enrichment Center at Angarsk, offering any country the opportunity to invest in the center, have a guaranteed supply of enriched fuel, and share in the profits, without spreading enrichment technology. Multinational approaches to the nuclear fuel cycle may be central to the future of nonproliferation and nuclear energy.

Source: angarsk-adm.ru

The Importance of the Back End of the Nuclear Fuel Cycle

Offers to take away spent fuel could be an even stronger incentive for states to rely on international fuel supply rather than on their own. Most states feel the commercial market already provides reliable supplies of fresh fuel, so backup supplies would have only a modest impact – but no state has yet solved the problem of spent fuel management, and offering to solve that problem would be an extremely attractive offer for many countries. Such offers, making it possible for states to establish nuclear energy programs without having to provide for a geologic repository of their own, could also eliminate an important barrier to broader use of nuclear energy around the world. Moreover, such offers would mean that the spread of nuclear energy need not also lead to a spread of sites around the world where plutonium-bearing spent fuel is stored indefinitely. An offer to manage countries' spent fuel would represent yet another expansion of the opportunities available to states under Article IV of the NPT. Indeed, the 2006 initiative by then-President Putin (now Russian Prime Minister) envisioned not just international enrichment centers but international centers for reprocessing and radioactive waste management as well, which would provide guaranteed services for all.

The politics of one country accepting “nuclear waste” from other countries are difficult – but it is still possible that they could be overcome. Options such as regional repositories, “fuel leasing” (in which the supplier provides an integrated service that includes providing fresh fuel and removing the spent fuel), “reactor leasing” (in which the supplier would provide the entire reactor, with its fuel, and then remove the entire facility, with the spent fuel, at the end of its life), or commercial repositories that would accept spent fuel from any state for an appropriate price should all be considered. If the politics can be overcome, such approaches could be a major contribution to both nonproliferation and the future of nuclear energy. (Later chapters in this report describe concepts for integrated reactor and fuel services focused on small and medium reactors in more detail.)

Russia and the United States should work together, and with other countries, to establish such mechanisms for international management of spent fuel, including the possibility of at least limited imports into both Russia and the United States, and possibly other countries as well. As the amount of spent fuel likely to be generated by “newcomer” states in the next few decades is very small, an offer to take back fuel used by newcomer states would have very little impact on the overall size of the nuclear waste problem that either Russia or the United States must manage. Once spent fuel has been imported, some countries may choose to reprocess and to recycle it, while others may choose to store it pending direct disposal.

Internationalizing the Nuclear Fuel Cycle

In the 1960s and 1970s, there was a significant trend toward internationalization of the nuclear fuel cycle. Germany, the Netherlands, and Great Britain established URENCO, a multilateral enrichment enterprise. France established Eurodif, another enrichment enterprise, with the financial, technical, and management participation of several other countries. Several countries joined in building the Eurochemic reprocessing plant in Belgium. The United States and the Soviet Union took back spent fuel from fuel they had provided.

Today, concepts for international approaches to the nuclear fuel cycle, from international fuel

banks to international centers for enrichment or reprocessing, are again being actively discussed. As noted earlier, Russia has launched the IUEC at Angarsk, and envisions this as only the first element of a global infrastructure of international facilities, which it sees as a central element of enabling a world of large-scale use of nuclear energy without significantly increased proliferation risk. As discussed in a later chapter, the availability of “cradle-to-grave” nuclear services could make it possible for countries which do not yet have a developed nuclear energy infrastructure to enjoy the benefits of nuclear energy safely and securely.

The central idea of the Russian initiative is the creation of a series of international centers, each under IAEA safeguards (and perhaps some greater degree of IAEA control), which would provide services to all without discrimination – but which would keep access to sensitive technology in the hands of its original holders.

As noted above, Russia has already established an International Uranium Enrichment Center (IUEC) at Angarsk. The IUEC is a legal entity which contracts with the Angarsk enrichment plant; the plant itself remains wholly Russian-owned and Russian-staffed, though it has been opened to IAEA safeguards. The basic principles of the IUEC include:

- Non-discriminatory membership with equal rights for all the participating countries (though Russia retains a majority share);
- Guaranteed access for all IUEC members to enrichment services or to enriched uranium product, specified in binding government-to-government agreements;
- Joint management and ownership of the IUEC by the member countries;
- IAEA safeguards on all IUEC nuclear materials; and
- A step-by-step approach to further development of the IUEC.

The IUEC was originally established by Russia and Kazakhstan. Armenia and Ukraine have since joined. Russia and the other IUEC members have discussed potential membership with a number of other countries as well.

Similarly, the U.S.-initiated Global Nuclear Energy Partnership (GNEP) envisioned possibilities for “cradle-to-grave” fuel services, guaranteeing access to both fresh fuel supply and spent fuel management, potentially provided by many nations working in partnership. In their totality, these initiatives were directed at making it possible to provide energy for countries all around the world without increasing proliferation or terrorism risks.

Although not formally part of any effort to internationalize the nuclear fuel cycle, several of the new enrichment facilities planned in the United States and elsewhere would have multinational ownership. Germany has proposed that the international community establish an enrichment plant on an internationally-controlled site located in a country outside any of the existing suppliers, for which the IAEA would have sole control over exports of low-enriched uranium; the plant itself would be built and operated commercially, by firms that already have enrichment technology (which would not be made available to the IAEA or others not in possession of enrichment technology).³⁶

³⁶ International Atomic Energy Agency, “Communication Received From the Resident Representative of Germany to the IAEA With Regard to the German Proposal on the Multilateralization of the Nuclear Fuel Cycle,” INFCIRC/704 (Vienna: IAEA, 4 May 2007).

There are clearly a wide range of different approaches to greater internationalization of the nuclear fuel cycle, which have different economic, nonproliferation, and other advantages and disadvantages.³⁷ Complex questions of national sovereignty and control over sensitive information and technology need to be addressed. Convincing states to place these facilities under international or multinational control will not be easy and special measures will be needed to ensure that multinational or international staffing and management of such facilities does not contribute to technology leakage. Over the long term, however, the advantages of moving the world's enrichment and reprocessing facilities toward multinational control appear to outweigh the disadvantages. Hence, over time, both the United States and Russia should move to place their enrichment and reprocessing facilities under increasing degrees of multinational or international control, while protecting the sensitive technologies these facilities use, and work with other countries to do likewise. For the



Centrifuge components removed from Libya after it agreed to end its nuclear program, which had been supplied by the global black-market nuclear technology network led by Pakistan's A.Q. Khan. Cooperation between Russia, the United States, and other countries will be essential to stop future black-market networks.

Source: United States Department of Energy Y-12 Nuclear Security Complex

long term, as Mohammed ElBaradei argued while serving as the Director-General of the IAEA, the goal should be a shift toward international or multinational control of all enrichment and reprocessing – perhaps starting with new facilities and eventually converting existing plants to some form of multinational ownership and control – “so that no one country has the exclusive capability to produce the material for nuclear weapons.”³⁸

More Proliferation-Resistant Approaches to Nuclear Energy

Different technical and institutional approaches to nuclear energy for the future could help manage the proliferation risks that might be posed by widespread use of nuclear energy. Some reactor and fuel cycle concepts, for example, require far less enrichment or reprocessing than

37 U.S. Committee on Internationalization of the Nuclear Fuel Cycle, National Academy of Sciences and National Research Council, and Russian Committee on Internationalization of the Nuclear Fuel Cycle, Russian Academy of Sciences, *Internationalization of the Nuclear Fuel Cycle: Goals, Strategies, and Challenges* (Washington, D.C.: National Academy Press, 2009).

38 Mohamed ElBaradei, “Reviving Nuclear Disarmament,” conference on “Achieving the Vision of a World Free of Nuclear Weapons, Oslo, 26 February 2008. For further discussion of international approaches to the nuclear fuel cycle, see U.S. Committee on Internationalization of the Nuclear Fuel Cycle, National Academy of Sciences and National Research Council, and Russian Committee on Internationalization of the Nuclear Fuel Cycle, Russian Academy of Sciences, *Internationalization of the Nuclear Fuel Cycle: Goals, Strategies, and Challenges* (Washington, D.C.: National Academy Press, 2009).

traditional once-through light-water reactors or fast reactors with plutonium reprocessing and recycling. Some concepts, ranging from certain advanced fast reactor concepts to thermal neutron concepts such as the molten salt reactor, might be able to dramatically extend nuclear fuel resources and reduce waste management burdens without ever conducting separations that would substantially contribute to proliferation risks. Other recycling concepts, by recycling plutonium together with actinides and possibly some fission products (so that it never appeared in the fuel cycle in a form usable in nuclear weapons without substantial processing), reducing some proliferation risks compared to traditional reprocessing, though still raising more proliferation risk than not processing the spent fuel at all.

One important set of concepts, described in more detail in a later chapter, would involve small and medium-sized factory-built reactors that might be deployed in many recipient countries and then returned to the factory when their service life was completed. Such reactors might be offered by an international consortium that would provide a “cradle-to-grave” service – providing the reactors, providing their fuel, providing expert teams to operate the reactors, and taking away the reactors and the spent fuel at the end of the effort. In some cases, such reactors might be designed with a sealed core, generating nuclear energy for 10-30 years with a single fuel load and then being removed, without the user country ever having access to the reactor’s fuel. Such facilities would do little to help recipient states build up nuclear expertise and infrastructure that might be useful for a nuclear weapons program. With concepts such as these, it might be possible to envision widespread deployment of nuclear energy around the world with little added risk of the spread of nuclear weapons.

Strengthening Enforcement

It is important that there be consequences when states violate their nonproliferation obligations. If states come to see that there are few penalties for failing to live up to their nonproliferation commitments, there is more risk that they will decide to pursue nuclear weapons. Russia and the United States have both supported a series of UN Security Council resolutions imposing sanctions on Iran, and other resolutions imposing sanctions on North Korea, for their failures to meet their nonproliferation obligations.

Russia and the United States, working with other members of UN Security Council, should make clear that major violations of the NPT represent threats to international peace and security justifying Security Council action. The two countries should work with other members of the Security Council to pass a resolution legally imposing safeguards obligations going well beyond the Additional Protocol on any state that substantially violates its safeguards obligations,³⁹ and lay out a menu of other possible actions that might be taken in future cases of violations of NPT obligations. Russia and the United States should cooperate in seeking to convince Syria to cooperate with the IAEA’s investigation of the alleged reactor bombed by Israel, and of the unexplained man-made uranium particles the IAEA detected at that site and another site in Syria – and if Syria continues to refuse, should work with other states to impose penalties on Syria.

³⁹See Pierre Goldschmidt, *IAEA Safeguards: Dealing Preemptively With Noncompliance* (Washington, D.C.: Carnegie Endowment for International Peace, 12 July 2008), http://belfercenter.ksg.harvard.edu/files/Goldschmidt_Dealing_Preventively_7-12-08.pdf (accessed 11 June 2010).

At the same time, the record suggests that sanctions are often not effective in convincing states to cooperate. Negotiation, including offering positive incentives for cooperation, can often be more successful. As noted above, Russia and the United States should work together to restart serious negotiations with Iran and with North Korea, in an effort to resolve the ongoing crises over their nuclear programs.

Reducing Demand for Nuclear Weapons

Ultimately, measures such as export controls and interdiction can only delay, not prevent, a determined state's effort to get nuclear weapons. The long-term success of the global nonproliferation regime depends on reducing demand for nuclear weapons. The effort to reduce demand has been more successful than is often recognized. Today there are only nine states with nuclear weapons – the same number as had such weapons 20 years ago – and all of the other states in the world are parties to the Nonproliferation Treaty, having agreed to forego nuclear weapons and accept verification of their compliance with that commitment. Never in human history has the most powerful weapon available to our species been so widely forsworn. Indeed, there are today more countries that started nuclear weapons programs and decided to abandon them than there are states with nuclear weapons – meaning that the international community's efforts to stem the spread of nuclear weapons succeed more often than they fail, even when states have started down the path to nuclear weapons.

But to continue this record of success in the face of the challenges described at the outset of this chapter will require additional action. The IAEA's Commission of Eminent Persons recommended a series of steps to help reduce demand for nuclear weapons:⁴⁰

- “Steps are needed to devalue nuclear weapons – that is, to reduce their strategic, reputational, and diplomatic value. Nuclear weapons states must renew their commitment to nuclear disarmament and take steps in that direction in the near term.”
- “The major powers should reaffirm their obligations under the UN Charter not to use or threaten to use force against states that have not attacked them and do not pose an imminent threat.”
- “All states should work to resolve major global or regional conflicts that drive demand for nuclear weapons.”
- “States should ratify and bring into force the nuclear weapons-free zones that have been negotiated, and negotiate to create additional such zones.”
- “All states should work together to begin building new structures of international security that can give increased confidence to states around the world that threats to their security will be effectively addressed.”

Fulfilling the Promise of Article VI

To achieve the dramatic growth needed for nuclear energy to make a major contribution to the global energy challenges of the 21st century without posing new proliferation dangers will require strong steps to strengthen the nonproliferation regime. But non-nuclear-weapon states are

40 Commission of Eminent Persons, *Reinforcing the Global Nuclear Order for Peace and Prosperity: The Role of the IAEA to 2020 and Beyond* (Vienna: International Atomic Energy Agency, May 2008), <http://www.iaea.org/NewsCenter/News/PDF/2020report0508.pdf> (accessed 8 June 2010).

not likely to agree to steps that impose additional constraints and inconveniences on them unless they see that the nuclear weapon states – particularly Russia and the United States, who hold the world's largest nuclear weapon stockpiles – are living up to their end of the nonproliferation bargain, including their Article VI obligation to negotiate in good faith toward nuclear disarmament. As a result, in the long term, a world of much more nuclear energy necessarily implies a world of many fewer nuclear weapons; the future of nuclear energy and of disarmament are inherently linked.

The NPT is based on a balance among the “three pillars” of the treaty – nonproliferation, nuclear disarmament, and peaceful uses of nuclear energy. The non-nuclear states insist on the priority of the second and third pillars, while the nuclear weapon states emphasize the importance of nonproliferation. Unless this contradiction can be addressed to the satisfaction of all parties, political support for the NPT regime may continue to erode. Proposals to strengthen global nonproliferation controls, such as those in this report, must be coupled with clear action on the disarmament agenda if they are not to lead to a backlash that could erode rather than strengthening the NPT.

Fortunately, at the May 2010 NPT Review Conference, after hard discussions, the parties to the NPT were able to overcome some of these disagreements and agree by consensus on an action plan on nuclear disarmament, endorsing the practical steps agreed to at the 2000 review and calling for the nuclear weapon states to “promptly engage” on reductions in the global stockpiles of all types of nuclear weapons, reducing the “role and significance” of nuclear weapons in military policies, steps to prevent the accidental or intentional use of nuclear weapons, and increased transparency and verifiability of nuclear reductions.⁴¹ Russia and the United States should take action to implement this agenda, by ratifying the New START treaty, beginning discussions of still deeper reductions, ratifying the CTB and working to bring it into force, working to begin negotiation of a verifiable fissile cutoff treaty, and taking other steps to build the conditions for the jointly agreed long-term objective of a world free of nuclear weapons.

41 2010 Review Conference, Actions 3-6.

SECTION II: DEVELOPING AND DEPLOYING THE NEXT GENERATION OF NUCLEAR ENERGY

5. REDUCING NUCLEAR COSTS AND BOTTLENECKS

Reducing the cost of nuclear power, while simultaneously improving safety, security, and proliferation-resistance, is an essential step to achieve large-scale nuclear energy growth around the world.

In the near term, the companies selling nuclear plants will play the central role in reducing costs. There may be opportunities for commercial collaborations between U.S. and Russian firms, just as Rosatom and Siemens are collaborating today.⁴²

There is a role for government in reducing the near-term costs of nuclear energy as well, in providing a stable and supportive policy environment that does not result in costly construction delays, and in taking steps to reduce the “cost of money” for the large capital investments required for today’s nuclear power plants. In Russia, for example, the government is planning to fund nuclear reactor construction directly from government budgets through 2015, with subsequent plants financed with the nuclear industry’s own funds plus private investments. In the United States, the government is planning to provide loan guarantees, regulatory risk insurance, and production tax credits for the first few new nuclear plants to be built, in the hope that building these initial plants will allow the industry to work through “first of a kind” problems and reduce risks and costs enough to allow subsequent reactors to be financed by the commercial market.

In addition, there may be roles for governments to play in reducing key bottlenecks that are driving up today’s nuclear energy costs – from shortages of appropriately certified vendors and trained personnel to capacity for the ultra-large steel forgings required by Generation III reactor designs. The United States and Russia should undertake a joint study of options for policies to address these bottlenecks and reduce costs.



Construction continues on the Olkiluoto nuclear plant in Finland, now years behind schedule and billions of dollars over budget. The United States and Russia should work with each other, and with other countries, to overcome bottlenecks in the global nuclear supply chain and develop new designs that would be simpler, cheaper, and quicker to build, including factory-built nuclear reactors. Source: BBC World Services

Over the longer term, new reactor concepts may make it possible to reduce nuclear energy costs and reduce the scale of the initial investments required to build nuclear facilities, while maintaining and even improving safety, security, and proliferation-resistance. Russia and the United States should cooperate in R&D designed to achieve these objectives.

⁴² Russian firms are already providing large supplies of uranium and enrichment services to the U.S. market as part of the U.S.-Russian HEU Purchase Agreement, and have negotiated contracts with U.S. utilities for the period after that agreement ends in 2013.

One potentially promising set of concepts, discussed in more detail later in this report, is smaller, factory-built reactors, with high levels of inherent safety and security, strong-proliferation resistance, and designs requiring few operating staff. These might potentially be marketed by an international consortium that could provide “cradle-to-grave” nuclear services – providing the reactors fully fuelled, operating them during their lifetimes, and taking away the reactor and its spent fuel when its operating lifetime was complete. Such an approach could potentially make nuclear power a viable option for a much broader array of countries than it is today, as countries making use of nuclear power would not need to develop an extensive infrastructure or a nuclear waste repository of their own. Economies of scale have driven nuclear designs toward today’s very large reactors, but small reactors might be able to make up in economies of factory production what they lose in economies of physical size. Groups in both the United States and Russia are pursuing a variety of concepts for small or medium-sized reactors, and the two countries (and other countries) should collaborate in an effort to establish whether and how such systems can provide cost-effective, safe, secure, and proliferation-resistant nuclear energy. If such an R&D effort produces viable design concepts that meet higher safety, security, and nonproliferation standards, the Russian and U.S. governments should encourage nuclear firms to form a full-services consortium providing such systems, making such policy adjustments as needed – including for return of the spent fuel from such facilities, as discussed later in this report.

6. MAKING NUCLEAR ENERGY BROADLY AVAILABLE

Today's highly complex 1-1.6 gigawatt-electric (GWe) light-water reactors (LWRs) are simply not suitable for many countries and regions around the world. As discussed earlier, building and operating them safely requires a substantial infrastructure of trained personnel, regulation, safety and security culture, and more, which many countries will not have for many years to come. Moreover, the electrical grids in many countries cannot support and do not require so much power concentrated at one location, and some countries would be hard-pressed to finance an investment of several billion dollars in a single power plant.

For nuclear energy to be available to a broader portion of the world's people, without posing undue risks as a result, would require nuclear energy systems that were simpler, smaller, more inherently safe, more inherently secure, and more inherently proliferation-resistant. A variety of concepts and designs for small and medium-sized reactors (SMRs) are being developed in Russia, the United States, and elsewhere, that may be able to accomplish some of these objectives. Buying such an SMR would represent a much smaller investment than buying a giant 1-1.6 GWe nuclear power plant such as those for sale on the international market today. (For countries whose electricity demand or power grid is too small to justify their own large baseload plants, shared regional nuclear plants – such as the plan being pursued by Lithuania and its neighbors -- may also be a cost-effective way to access nuclear energy.)

A New International Consortium for “Cradle-to-Grave” Nuclear Services

Russia and the United States, working with other suppliers, should establish a multinational joint venture to provide an integrated “cradle-to-grave” nuclear service, providing: (a) factory-built medium and small reactors; (b) fuel for these facilities (which might be built in to the reactors from the outset); (c) expert operators to operate these facilities safely; and (d) removal of the reactors and spent fuel at the end of their lives.⁴³ These reactors could be deployed in many countries. These reactors should be designed for high levels of inherent safety, security, and proliferation resistance. Recipient states would have no need for either enrichment or reprocessing facilities, greatly reducing the proliferation impact of operating these facilities in many countries. Economies of factory production might help counteract the reduced economies of scale such SMRs would have; and Russia, the United States, and other participating countries should also pursue R&D to reduce the costs of such SMRs over time. The participants in the consortium might also establish mechanisms to provide low-cost financing for such facilities. Potentially, such comprehensive nuclear services might prove to be so attractive that most of the states pursuing nuclear energy would choose to do so by this route, which would have significant safety, security, and nonproliferation benefits.

This consortium would be based on far-reaching international cooperation, combining the

43 For a discussion, see Evgeniy P. Velikhov, Vyacheslav P. Kuznetsov, and Vladimir P. Shmelev, “Proposal for Nuclear Power Development on the Basis of Serial Medium Capacity NPP in Non-Proliferation Conditions,” presented at the “International Conference on Nuclear Disarmament,” Oslo, Norway, 26-27 February 2008, http://disarmament.nrpa.no/wp-content/uploads/2008/02/Paper_Kuznetsov.pdf (accessed 13 June 2010). For a useful summary of the current status of small and medium reactor designs, see World Nuclear Association, “Small Nuclear Reactors” (London: World Nuclear Association, updated June 2010), <http://www.world-nuclear.org/info/inf33.html> (accessed 14 June 2010).

best scientific, technological and industrial capabilities of each participant, along with their natural and financial resources. The members of the consortium would welcome other states to join the effort whenever their contribution could strengthen the overall project. Over time, the consortium – which might be called an “International Project for Nuclear Energy” – might be broadened to encompass all aspects of the nuclear fuel cycle, from mining of uranium to disposal of radioactive wastes. Such a multinational consortium might ultimately come under the aegis of the IAEA, or it might remain a commercial venture with several countries participating. The special report of the Commission of Eminent Persons presented at the General IAEA Conference in September of 2008, recommended that IAEA member states, the nuclear industry, and the IAEA cooperate in creating such multilateral consortia.⁴⁴ As an initial step, Russia, the United States, and other interested countries could begin working out a set of agreed principles and approaches for the supply of small and medium reactors and “cradle-to-grave” services for them; this would make it possible to create a loose confederation operating on similar approaches, even if individual companies initially chose to promote their own designs rather than joining in a joint venture.

This multinational consortium would make nuclear energy available to all states that met agreed criteria. Of course, there will continue to be states for which nuclear reactors are not appropriate – states in violation of their nonproliferation obligations, states suffering major political unrest or civil wars, failing states lacking well-functioning central governments, and the like. The participants in the consortium would develop appropriate export criteria for the project, and also work out agreed safety and security standards.

With simplified reactors requiring only a small staff, and operators provided from an international operating company participating in the consortium, it would be possible for states to make use of nuclear power safely even if they did not possess the qualified personnel and infrastructure necessary to build and operate reactors themselves. Each state using such reactors, however, would need to develop effective nuclear safety regulation (though the necessary regulation might be much less complex for small reactors with a high degree of inherent safety than they have to be for today’s large LWRs). As recommended earlier, Russia, the United States, other suppliers, and the IAEA should cooperate to help ensure that all “newcomer” states are able to establish effective nuclear regulatory systems before their first nuclear power plants come on-line.

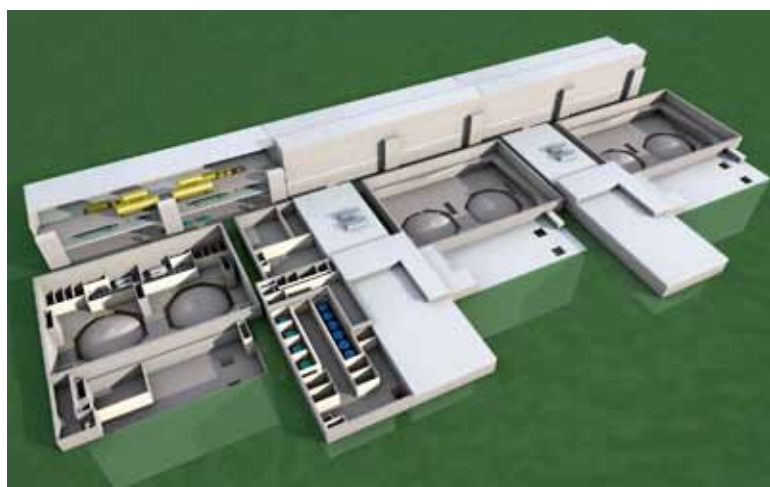
It would be important to include “safeguards by design” principles into the reactors supplied by such a consortium, designing them so that safeguards could be applied simply and easily, with unified methods and procedures for all of them.

A competitive struggle for new markets for SMRs could lead suppliers to make unwise concessions on safety, security, or nonproliferation requirements, to underestimate project costs, or to other undesirable consequences. Pulling SMR suppliers into a common consortium – or at least actively coordinating common positions among them – could help reduce these risks. Even if some suppliers do not participate, a consortium that combined the strongest capabilities of several of the leading supplier countries might be able to offer a service so attractive that it could out-compete even less scrupulous suppliers. Such an international cooperative approach would pose far fewer risks to the world than widespread and unregulated marketing of nuclear facilities

44 Commission of Eminent Persons, *Reinforcing the Global Nuclear Order for Peace and Prosperity: The Role of the IAEA to 2020 and Beyond* (Vienna: International Atomic Energy Agency, May 2008), <http://www.iaea.org/NewsCenter/News/PDF/2020report0508.pdf> (accessed 8 June 2010).

by many countries, including countries with less experience in achieving high standards of safety and security.

Forming a strong multinational consortium might serve the interests of both suppliers and recipients. For suppliers, the consortium could provide a cooperative framework within which they could compete in a less chaotic and more predictable way, with decisions made by all and the long-term benefits accruing to the entire consortium. For the recipients, if the consortium includes a large fraction of the major fuel cycle and reactor suppliers, it would be possible to organize the business so that each commodity or service could be delivered by the participant that could deliver it with the best combination of price and quality, making it possible for the consortium as a whole to offer a competitive service while generating profits to be shared by all



Simplified small and medium reactors with high levels of inherent safety, security, and proliferation-resistance could make nuclear energy available to countries with smaller electrical grids and less infrastructure than is possible for today's huge and complex nuclear plants – and could break the needed investments into more manageable pieces. Here, an artist's concept envisions six units of the 125 MWe “mPower” design from B&W strung together into a 750 MWe power plant.

Source: Babcock & Wilcox Company

participants. Recipient would not need to invest in developing and building their own reactor designs or their own fuel cycle facilities if they did not choose to do so. Over time, the consortium could welcome new members, as additional states developed to the point where they could make substantial contributions to the effort and wished to join. The consortium would not infringe on any state's Article IV rights; indeed, it would expand the opportunities available under Article IV, making nuclear energy more easily available to a broader range of countries than ever before, with a broader set of guaranteed services available.

7. MAKING NUCLEAR ENERGY AVAILABLE FOR A BROADER ARRAY OF PURPOSES

Today, nuclear energy provides baseload electricity in 30 countries, providing some 15% of the electricity generated worldwide. Electricity's share in global energy use may well grow in the future, particularly if electric vehicles become widespread. But in the future it may also be possible to use the heat from nuclear reactors for a wide variety of purposes going well beyond baseload electricity supply. Such an expansion of nuclear energy's potential missions could allow nuclear energy to play a larger part in meeting the energy challenges of the 21st century.

The two additional purposes for nuclear energy that have been explored in most detail are desalination (which was part of the purpose of the BN-350 fast reactor in Kazakhstan before it was shut down) and production of hydrogen as an energy carrier for vehicles, stationary fuel cells, and the like (or as a contribution to synthesis of other transportation fuels from biomass or other sources). In both cases, one could imagine reactors that would produce electricity during the day when demand was high, and use much of their energy to produce hydrogen or desalinate water at night when electricity demand was lower, potentially improving the economics of the overall system.

Heat from nuclear plants could also contribute to a wide variety of other energy needs:

- Process heat for a wide range of industrial processes.
- Heat to provide the energy needed for oil refineries, biofuel refineries, or coal-to-liquids plants, so that more of the input stock would end up as refined products rather than being burned to fuel the refining.
- Energy to pressurize natural gas or CO₂ for transport, and to separate the two gases when they are recovered together.
- Heat to help recover oil from tar sands and oil shales, or syn-gas from coal beds (lessening the greenhouse gas releases of traditional methods for providing this heat).
- Providing backup electricity for intermittent sources such as solar and wind (with the nuclear plant generating a steady energy supply, but potentially switching that supply to electricity production when the sun does not shine or the wind does not blow, and producing hydrogen the remainder of the time).

Russia, the United States, and other countries should cooperate to explore such possibilities, and should undertake both joint systems analyses and joint R&D on those concepts that appear most promising.



Tiny fuel particles such as this “TRISO” (tristructural isotropic) fuel pellet are used in high-temperature gas reactor designs, allowing the fuel to operate at very high temperatures without melting. These high temperatures make it possible for such reactors to provide process heat for a wide range of industrial applications (as well as hydrogen production), potentially helping to make nuclear energy useful for a broad range of purposes beyond generating electricity.

Source: U.S. Department of Energy

8. FUELING NUCLEAR GROWTH

Large-scale nuclear growth would require a large expansion of nuclear fuel supply. One of the most remarkable features of nuclear energy, however, is how much energy it can make from a modest amount of fuel. A one-gigawatt coal plant requires an 80-car coal train every day. A one-gigawatt nuclear plant requires roughly half of one car of fuel once a year (though a considerably larger amount of uranium must be mined to produce that half-car of enriched fabricated fuel).

Today's world nuclear energy infrastructure uses just over 60,000 tons of natural uranium per year.⁴⁵ The International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) estimate that there are 5.4 million tons of known or inferred uranium resources available at production costs of \$130 per kilogram of uranium (kgU) or less, and at least another 900,000 tons available costs up to \$260/kgU, given today's technology and geologic knowledge.⁴⁶ An additional 10.4 million tons probably exists, but requires more exploration to confirm.⁴⁷ The 5.4 million tons of known or inferred resources increased by 15% just from 2005-2007, because of reassessments of what was recoverable in known deposits and increased exploration resulting from increased prices; it then declined by 1% from 2007 to 2009 as increasing prices made less of the uranium appear to be available within the price range. Even when prices were low and little exploration was carried out in the 1990s and the early years of the 21st century, estimated uranium resources increased more rapidly than uranium was consumed.⁴⁸ For the long term how much uranium will be recoverable at what price is not well understood, though it is likely that recoverable resources will increase as technology improves and new deposits are identified.

Most reactors today operate on a “once-through” fuel cycle, using low-enriched uranium (LEU) which is slated for disposal after use. This fuel cycle uses only about 1% of the energy potentially available in uranium. Other fuel cycles, particularly those involving recycling in fast reactors, can “breed” plutonium that can be used as fuel from neutron absorption in U-238 (representing more than 99% of natural uranium). Thorium can be transmuted into U-233 in a similar way, allowing thorium (which is even more abundant than uranium) to be used as a fuel as well. A recent study by a joint committee of the Russian and U.S. Academies of Sciences concluded that in most cases, the reprocessing required for such recycling approaches “is not economic under

45 Organization for Economic Cooperation and Development, Nuclear Energy Agency, and International Atomic Energy Agency, *Uranium 2009: Resources, Production, and Demand* (Paris: OECD-NEA, 2010), p. 59.

46 This total of “identified resources” is the sum of “reasonably assured resources” (RAR) and “inferred resources.” See NEA/IAEA, *Uranium 2009*, p. 10, 15-33. The quantity of resources available in the higher price range is likely to be substantially understated, as (a) uranium prices well below this level have offered little incentive for companies to explore for resources in this cost range, and (b) only a modest number of countries report resources in this cost range.

47 These “undiscovered resources” are the sum of “prognosticated resources” (those “expected to occur in known uranium provinces, generally supported by some direct evidence”) and “speculative resources” (those “expected to occur in geological provinces that may host uranium deposits”). These are likely understated, as only a modest number of countries report resources in both of these categories. See NEA/IAEA, *Uranium 2009*, pp. 27-28.

48 In 1997, the estimate for the sum of RAR and inferred resources at \$80/kgU or less was 3.085 million tons, while in 2005 it was 3.804 million tons, an increase of 23% in eight years, despite the very low level of investment in uranium exploration until the end of that period. See Organization for Economic Cooperation and Development, Nuclear Energy Agency, and International Atomic Energy Agency, *Uranium 1997: Resources, Production, and Demand* (Paris: OECD-NEA, 1998), and *Uranium 2005: Resources, Production, and Demand* (Paris: OECD-NEA, 2006). Indeed, the press release for the 2005 edition was entitled: “Uranium: plenty to sustain growth of nuclear power.”

current conditions,” and that since “uranium enrichment and spent fuel reprocessing are the key technologies that enable countries to produce direct-use materials for nuclear weapons,” so that “the more countries to which either technology (enrichment or reprocessing) spreads, the greater the proliferation risks.”⁴⁹ For these reasons, the United States and a number of other countries have emphasized a once-through fuel cycle without recycling; Russia and a number of other countries have emphasized reprocessing and recycling.

Russia has decided to embark on development of a “new technological platform” for nuclear energy, focused on advanced approaches to fast reactors and recycling designed to extend uranium resources.⁵⁰ The United States is also pursuing research and development on fast reactors and recycling, both for waste minimization and for resource extension, but currently remains committed to an open fuel cycle.⁵¹ Both countries are working on spent fuel processing approaches intended to offer lower costs and improved proliferation-resistance.

Whether, when, and on what scale nuclear breeder reactors will be needed depends on how rapidly nuclear energy grows and how abundant uranium supplies prove to be. If nuclear energy grows very rapidly and uranium supplies turn out to be very limited, large-scale deployment of reactors designed to breed more fuel from uranium or thorium could be needed in the second half of the 21st century (which, in turn, would require limited deployment sooner, to establish experience and demonstrate improved technologies). If nuclear energy grows more slowly or uranium proves to be more abundant, large-scale deployment of breeder reactors might not be necessary for a much longer time.⁵² The record of other



Reactor vessel for the BN-800 fast neutron reactor, under construction in Russia. When large-scale deployment of such plutonium-breeding reactors will be needed depends on how much uranium ultimately proves to be economically recoverable and how fast nuclear energy grows in the future.
Source: JSC Machine-Building Plant ZiO-Podolsk.

49 Commission of Eminent Persons, *Reinforcing the Global Nuclear Order for Peace and Prosperity: The Role of the IAEA to 2020 and Beyond* (Vienna: International Atomic Energy Agency, May 2008), <http://www.iaea.org/NewsCenter/News/PDF/2020report0508.pdf> (accessed 8 June 2010).

50 Federal Target Program “New-Generation Nuclear Energy Technologies for 2010-2015 and for Perspective to 2020,” adopted by Russian government decree No. 50, 21 January 2010.

51 For current U.S. priorities, see U.S. Department of Energy, Office of Nuclear Energy, *Nuclear Energy Research and Development Roadmap: Report to Congress* (Washington, D.C.: April 2010), http://nuclear.gov/pdfFiles/NuclearEnergy_Roadmap_Final.pdf (accessed 14 June 2010).

52 For summaries of some of the arguments, see, for example, Evgeniy P. Velikhov, Andrei Yu. Gagarinski, Stanislav A. Subbotin, and V.F. Tsibulski, *Russia in the World Energy of the XXI Century* (Moscow: Izdat Nuclear Science and Engineering Publishers, 2006); John Deutch and Ernest J. Moniz, co-chairs, *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, MA: Massachusetts Institute of Technology, 2003) <http://web.mit.edu/nuclearpower/> (accessed 20 May 2010); Matthew Bunn, Steve Fetter, John P. Holdren, and Bob van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel* (Cambridge,

minerals throughout the 20th century suggests that as geologic exploration proceeds and mining technology improves, the quantity of uranium that is economically recoverable is likely to expand substantially beyond the IAEA/NEA figures quoted above; if this is correct, it might postpone the need for large-scale deployment of breeder reactors into the 22nd century.⁵³ Whatever the conclusion for the long term, to the extent practicable, reprocessing of spent fuel should be done when the materials the spent fuel contains are actually needed as fuel, rather than accumulating additional stockpiles of separated plutonium waiting for years or decades before being fabricated into fuel.

For now, there continue to be substantial disagreements over whether and when commercialization of fast neutron breeder reactors will be justified. There is much broader agreement, however, that it is worthwhile to pursue additional research and development to explore technologies that might someday provide lower-cost fast-neutron reactors and fuel cycles with improved nonproliferation and safety characteristics. Russia and the United States should:

- Jointly sponsor research to better understand global uranium supplies available in the near and long-term, which are a key driver of when or whether deployment of fast-neutron breeder reactors will be needed. (Because industry has little incentive to look for supplies that will not be needed for 20 years or more, governments will have to invest in such long-term resource assessments.)
- Pursue joint R&D on a variety of approaches to extending nuclear fuel resources, including both once-through and recycling approaches. This R&D should include fast reactors with recycling, fast reactors that might be able to breed plutonium and consume it without reprocessing, and thermal reactors and fuel cycle systems potentially capable of substantially extending fuel resources (such as molten salt reactors). It should include thorium approaches as well as uranium approaches. And it should incorporate safety, security against sabotage, security against theft, and proliferation-resistance as key parameters throughout the life-cycle of the concepts examined. Concepts for extending fuel resources and for easing nuclear waste management burdens (discussed in the next section) should be pursued in an integrated way.

MA: Project on Managing the Atom, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, December 2003), <http://www.belfercenter.org/files/repro-report.pdf> (accessed 20 May 2010).

⁵³ For an authoritative recent review, see Erich A. Schneider and William C. Sailor, "Long-Term Uranium Supply Estimates," *Nuclear Technology*, Vol. 162 (June 2008), pp. 379-387.

9. MANAGING NUCLEAR WASTES

Public concern over whether nuclear wastes can be managed safely is a major constraint on large-scale expansion of nuclear power. No country has yet opened a permanent geologic repository for spent nuclear fuel or high-level wastes (HLW).⁵⁴ Russia and the United States, in particular, face extensive challenges in cleaning up the nuclear legacies of their Cold War arms competition, with numerous contaminated sites and large volumes of HLW and other waste materials that must be managed. U.S. President Barack Obama has canceled the proposed Yucca Mountain nuclear waste repository and established a Blue-Ribbon Commission to examine approaches to managing U.S. spent fuel and nuclear waste. Russia has not yet chosen a final site for a geologic nuclear waste repository. Only eight countries today possess underground research laboratories to explore approaches to high-level waste disposal.

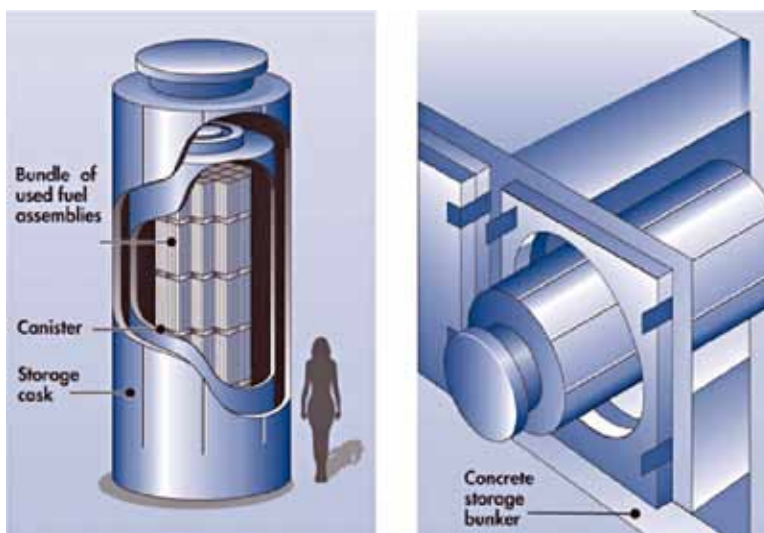
Fortunately, dry casks and steel canisters are proven and cost-effective technologies that can safely store spent fuel and vitrified HLW for decades. This makes it possible to take a careful, deliberate approach to final disposal of nuclear wastes, allowing time for the development of improved technologies and institutional approaches.

Currently, countries operating nuclear power facilities have chosen three basic approaches to managing their spent nuclear fuel:

1. Storage followed by direct geologic disposal (the “open” fuel cycle).
2. Reprocessing and recycling of the recovered plutonium and uranium (the first step of a “closed” fuel cycle).
3. Storage while postponing final decisions on disposal or reprocessing.

Intermediate storage is needed for efficient management of any of these options.

To date, as noted earlier, the United States has favored an open fuel cycle. Russia considers most of its spent nuclear fuel as a resource to be reprocessed, though for some spent fuel it has deferred a decision and left open the possibility of direct disposal.



Dry storage casks, such as those pictured here, provide a safe and cost-effective approach to managing spent fuel that will last for decades, offering time to site and develop repositories and to research and develop improved approaches to managing spent fuel.

Source: U.S. Nuclear Regulatory Commission

⁵⁴ The United States, however, is successfully operating the Waste Isolation Pilot Plant (WIPP), a repository for plutonium-contaminated wastes in a salt deposit in New Mexico.

Russia and the United States should:

- Focus in the near term on establishing sufficient safe storage capacity for their spent fuel and HLW, including both at-reactor and away-from-reactor storage facilities.
- Cooperate in developing and implementing appropriate technologies and approaches for cleaning contaminated nuclear sites and managing more problematic types of nuclear wastes.
- Reaffirm the international consensus that geologic disposal is the best final approach for nuclear wastes, and will be required for both once-through and closed fuel cycles.
- Expand joint R&D on repository science and technology.
- Expand joint R&D to improve both once-through and closed fuel cycles, including their waste management characteristics. In particular, analyses should be explored to determine whether there are options that might make it possible to fission or transmute long-lived radionuclides without ever separating plutonium or U-233 into weapons-usable forms, and without building up infrastructure or expertise that would contribute substantially to nuclear weapons programs.

As noted in earlier chapters, Russia and the United States should also actively work to develop and to implement international cooperative approaches to the back end of the nuclear fuel cycle. These would include concepts such as fuel leasing (providing fresh fuel with a promise to take back the irradiated fuel), reactor leasing, and international or regional repositories. Countries pursuing the reprocessing route might choose to establish regional or international reprocessing facilities. International approaches that allowed countries to enjoy the benefits of nuclear energy without needing their own reprocessing or waste management facilities could have major benefits for both the future of nuclear energy and stemming the spread of nuclear weapons, and would be very much in line with President Putin's concept of a global nuclear power infrastructure. As part of this overall effort, Russia and the United States should both be willing to take limited quantities of spent power reactor fuel from other countries when doing so would promote national and international security.

10. AREAS FOR JOINT R&D

Russia and the United States have some of the strongest groups of nuclear scientists and engineers in the world. Experts from both countries have important ideas and insights to offer, and in some areas the two countries' strengths are complementary. Both countries are investing hundreds of millions of dollars in nuclear R&D, and partly pooling these resources in a common effort could accelerate progress. U.S. and Russian experts should exchange experience and results, explore joint designs, design and conduct joint experiments, and more. Making use of experimental facilities in both countries – especially the more extensive facilities available in Russia – could allow both countries to share the costs of building and maintaining such facilities. Cooperation in developing improved concepts for nuclear energy would serve both U.S. and Russian national interests. Russia and the United States should expand joint nuclear R&D efforts, focused on addressing key issues for the future of nuclear energy – cost, safety, security, proliferation resistance, resource utilization, and waste management. Where appropriate, this work should be done in partnership with other countries as well, under the aegis of the Generation IV and Innovative Reactors and Fuel Cycles Project (INPRO) efforts, but we recommend a significant expansion compared to the level of joint U.S.-Russian work now taking place in those efforts. Key potential areas for joint R&D are listed below.

Advanced Modeling and Simulation Technologies

Advances in simulation and modeling can accelerate the pace of nuclear energy development, making it possible to explore new concepts, assess which avenues are most promising, and examine the effect of varying particular parameters far more quickly and effectively than could otherwise be possible. Advanced modeling and simulation can also help make use of the data generated by testing and laboratory experiments more effectively. Russia and the United States should exchange key safety and modeling codes, conduct benchmarking exercises to identify the differences between them, and carry out joint experiments to validate these models.

Currently on the U.S. side, much of the most significant information that would provide the basis for this joint work is subject to export controls. In our judgment, such information could be exchanged between the United States and Russia without contributing to security risks to either country. The United States should review the controls over this information with a view to exchanging the information needed for fruitful collaborations in this area.

Reduced Nuclear Energy Costs

Estimated capital costs of nuclear power plants have increased substantially in the last decade. New technologies may have the potential to reduce costs significantly. In the near term, new integrated and modular manufacturing approaches can make it possible to build more of nuclear reactors on assembly lines and less at the construction sites, reducing both costs and the time required for construction. Over the longer term, new reactor concepts and radically simplified designs could reduce costs significantly, if R&D shows them to be viable. Russia and the United States should jointly explore such possibilities.

Factory-Built Reactors for Widespread Deployment

As discussed in previous chapters, a multinational consortium providing factory-built reactors with high levels of inherent safety, high security, and high proliferation-resistance could be a central element of the future of nuclear energy. Russia and the United States should pursue cooperative R&D on such factory-built reactors, with a particular focus on concepts that could reduce their cost and seize the potential cost advantages of assembly-line manufacturing.⁵⁵ They should jointly establish safety, security, and proliferation-resistance goals for such reactors and develop technical and institutional approaches that would allow these goals to be met.

At the 2009 Winter Meeting of the American Nuclear Society (ANS), ANS and the Nuclear Society of Russia signed a joint statement on bilateral cooperation in the field of nuclear energy with a focus on developing small and medium nuclear power facilities.

Open-Cycle and Closed-Cycle Approaches to Extending Resources

Russia and the United States should pursue a range of joint R&D projects focused on ensuring that there will be sufficient resources to fuel large-scale nuclear growth for decades to come.

First, to better understand when further resource extension might be needed, Russia and the United States should undertake a detailed examination of how much uranium may be available at what prices worldwide as technology and geologic knowledge develop in the future. This examination should include consideration of what approaches might make it cost-effective to recover uranium from a wide range of unconventional resources. Russia and the United States should cooperate with Japan and other leaders in the field to explore how practical it might someday be to recover the huge but very dilute resources of uranium from seawater.

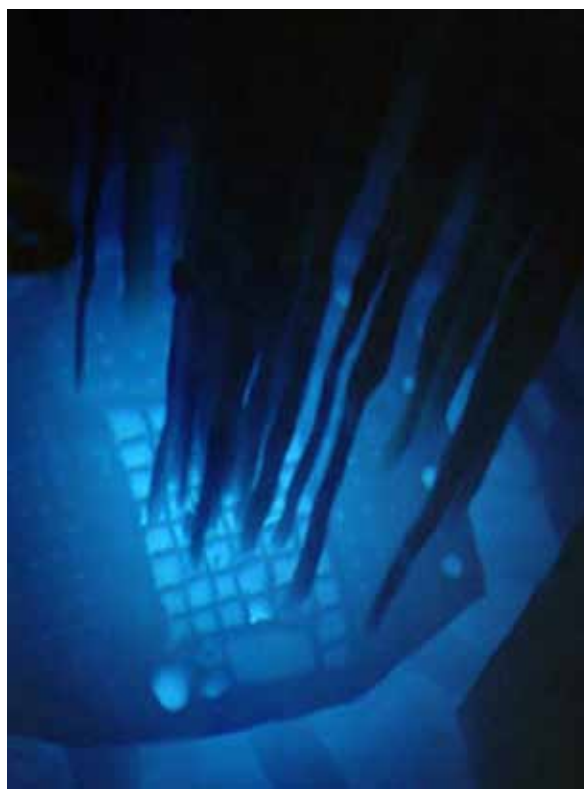
Second, joint projects could explore a range of fast-neutron reactor concepts utilizing a variety of coolants, fuel types, and recycling approaches. The United States, for example, has put high priority on metal fuels for the next step beyond oxide fuels, while Russia is now focused heavily on nitride fuels; Russian and U.S. experts should jointly explore and experiment with the advantages and disadvantages of both these fuel types, along with others. Similarly, both Russian and U.S. experts have developed concepts for pyroprocessing of spent fuel, but there are enough differences in approach and experience that each could contribute to the other's efforts. In this broad exploration, options that include recycling should focus on advanced concepts for proliferation resistance, including systems in which the fuel materials are intensively radioactive and must be handled behind heavy shielding with no human access throughout the fuel cycle. Russian and U.S. experts could work together on the full range of issues that need to be addressed, including approaches to inherent safety; advanced materials capable of withstanding intense neutron radiation and high temperatures; fabrication processes for fuels containing plutonium and other transuranics and fission products; advanced spent fuel processing technologies (including not only aqueous and molten salt technologies but less explored approaches as well, from plasma processing to fluoride volatility); and more. These R&D efforts should include both uranium and thorium-based systems. Fast neutron concepts without separations – where plutonium is bred

⁵⁵ For a useful summary of the current status of small and medium reactor designs, see World Nuclear Association, "Small Nuclear Reactors" (London: World Nuclear Association, updated June 2010), <http://www.world-nuclear.org/info/inf33.html> (accessed 14 June 2010).

in the reactor and fissioned without any form of reprocessing – should also be explored, as these may offer substantial resource extension without the proliferation risks associated with many recycling technologies.

Third, thermal neutron concepts that could substantially extend uranium resources should be explored as well, including concepts that offer very high burnup, and concepts that make it possible to produce fissile isotopes from non-fissile materials and sustain the reaction without ever separating weapons-usable nuclear material. Prominent among the latter concepts is the molten salt reactor, described below. Russia and the United States continue their joint development of thorium-uranium fuels for existing light-water reactors (LWRs) and bring them to commercial deployment; while these offer only modest extension of the uranium resource, they have other advantages that may make them attractive.

All of these concepts should be developed as integrated systems, including reactor, recycling, and fuel technologies, so that appropriate trade-offs and optimizations can be made. The R&D efforts should incorporate safety, security against sabotage, security against theft, and proliferation-resistance as key parameters throughout the life-cycle of the concepts examined. The research agenda should be driven by in-depth system analyses covering the complete life-cycle of proposed systems, and a full set of criteria for comparison. Indeed, techniques for such wide-ranging system analyses are themselves potentially a fruitful area for further cooperation. Concepts for extending fuel resources and for easing nuclear waste management burdens (discussed in the next section) should be pursued in an integrated way. A joint committee of U.S. and Russian experts has proposed useful criteria for judging such fuel cycle approaches, and discussed some of the approaches being developed in Russia and the United States.⁵⁶



Thorium-uranium fuel assemblies being tested at the Kurchatov Institute in a joint Russian-American project could reduce nuclear waste and make spent fuel more proliferation resistant – a good example of the potential for U.S.-Russian cooperation in nuclear energy research and development.

Source: Lightbridge

Waste Management and Geologic Disposal

Russia and the United States should jointly explore a range of key issues in waste management and geologic disposal. This expanded joint R&D effort should include:

- Repository science and technology for a range of potential repository geologies and designs,

⁵⁶ U.S. Committee on Internationalization of the Nuclear Fuel Cycle, National Academy of Sciences and National Research Council, and Russian Committee on Internationalization of the Nuclear Fuel Cycle, Russian Academy of Sciences, *Internationalization of the Nuclear Fuel Cycle: Goals, Strategies, and Challenges* (Washington, D.C.: National Academy Press, 2009). pp. 57-84.

including possibilities to maintain the radioactive wastes in retrievable forms and retrieve them if necessary;

- Alternatives to mined geologic repositories, particularly deep boreholes;⁵⁷
- Approaches to improving waste-management characteristics in both once-through and closed fuel cycles (including analyses to explore whether there are options that might make it possible to fission or transmute long-lived radionuclides without ever separating plutonium or U-233 into weapons-usable forms, and without building up infrastructure or expertise that would contribute substantially to nuclear weapons programs).

As just noted, approaches to extending fuel resources and to improving waste management should be explored as integrated systems, and should include both uranium and thorium concepts.

High-Temperature Gas-Cooled Reactors (HTGRs)

In the 1960s to the 1980s, five HTGRs were built and operated in the United States and Europe, the largest with capacities of up to 300 MWe. The shutdown of the last of these facilities in the 1980s greatly slowed the development of this reactor technology. Russia also possesses scientific developments on HTGRs, including detailed designs intended for power applications such as high-potential process heat (950°C) and electricity production, as well as an operating prototype of a space propulsion facility with a unique outlet temperature of 3000°K. Currently Japan and China are building or operating small experimental facilities of this type, and China is building commercial demonstration modules; South Africa has developed a design of a pebble-bed HTGR (though it has suspended construction of a prototype for lack of funds); the United States is considering construction of a very high-temperature gas reactor in the Next Generation Nuclear Plant project; and very high-temperature gas reactors are among the technologies that several countries are cooperating to develop in the Generation IV International Forum.

Russia and the United States have been cooperating for years in what has now become a multinational project to design and to demonstrate key technologies for an HTGR sometimes also known as a gas turbine modular helium reactor (GT-MHR). The Russian Research Center “Kurchatov Institute” and the General Atomics company have played leading roles in this work, and both the U.S. and Russian governments have provided funding, in a partnership-based approach similar to what this report recommends for other U.S.-Russian cooperative efforts.

Russia and the United States, along with other interested countries, should collaborate in financing and building a demonstration GT-MHR facility, designed to build the confidence necessary for commercial sales.

Molten Salt Reactors

If relevant technical challenges could be addressed, molten salt reactors (MSRs) could have attractive features for fueling large-scale nuclear deployment, for proliferation resistance, and for

⁵⁷ See, for example, discussion in John Deutch and Ernest J. Moniz, co-chairs, *The Future of Nuclear Power: An Interdisciplinary MIT Study* (Cambridge, MA: Massachusetts Institute of Technology, 2003) <http://web.mit.edu/nuclearpower/> (accessed 20 May 2010), pp. 56-57.

transmuting long-lived species in nuclear waste.⁵⁸ Russia and the United States have both explored MSR concepts, as have several other countries. Russia and the United States should launch a joint R&D effort to explore whether MSRs can be developed into a commercially viable option for large-scale deployment.

Reactors for Additional Purposes Beyond Electricity Generation

As discussed in an earlier chapter, there are a broad range of possibilities for heat from nuclear reactors to provide the energy for desalination, hydrogen production, refining, and a wide range of other industrial processes. There are also possibilities for nuclear plants to be built in tandem with intermittent sources such as wind or solar facilities providing electricity when it was needed and using their energy to produce other products when their electricity was not required.

Russia, the United States, and other countries should launch joint efforts to explore such possibilities, and should undertake both joint systems analyses and joint R&D on those concepts that appear most promising.

Research on New Regulatory Approaches for Innovative Reactors

As noted in an earlier chapter, in many countries nuclear regulations have been written on the basis of experience with existing reactor designs. For innovative reactor designs based on very different principles, new approaches are likely to be needed. Research to support development of appropriate regulations for advanced reactor designs could be an important area for cooperation between Russian and U.S. experts, along with experts from other countries. Such research would examine existing codes, standards, and regulations, identify what changes may be needed, and explore the technical areas needed to understand what regulations and standards would be most effective.

Advanced Safeguards and Security Technologies

Finally, to meet the safeguards challenges of the future and protect the global nuclear enterprise from terrorists while minimizing costs, a new generation of safeguards and security technologies will be needed.⁵⁹ The United States has launched the Next-Generation Safeguards Initiative in part to fill this need, though it does not cover improved technologies for nuclear security. Russia and the United States should cooperate to develop a wide-range of new safeguards and security technologies. This effort should work closely with the IAEA and with nuclear security operators to ensure that the R&D is focused on the highest-priority needs, and to ensure that technologies are successfully transitioned to deployment once developed. This effort should include approaches to achieving effective safeguards and security by design in new nuclear energy systems.

⁵⁸ See, for example, discussion in Harold Feiveson, Alexander Glaser, Marvin Miller, and Lawrence Scheinman, *Can Future Nuclear Power be Made Proliferation-Resistant?* (College Park: Center for International Security Studies at Maryland, School of Public Policy, University of Maryland, July 2008), http://www.cissm.umd.edu/papers/files/future_nuclear_power.pdf (accessed 15 June 2010), p. 14 and pp. 46-51.

⁵⁹ Nuclear Energy Study Group, American Physical Society Panel on Public Affairs, *Nuclear Power and Proliferation Resistance: Securing Benefits, Limiting Risk* (Washington, D.C.: American Physical Society, May 2005), <http://www.aps.org/policy/reports/popa-reports/proliferation-resistance/upload/proliferation.pdf> (accessed 15 June 2010).

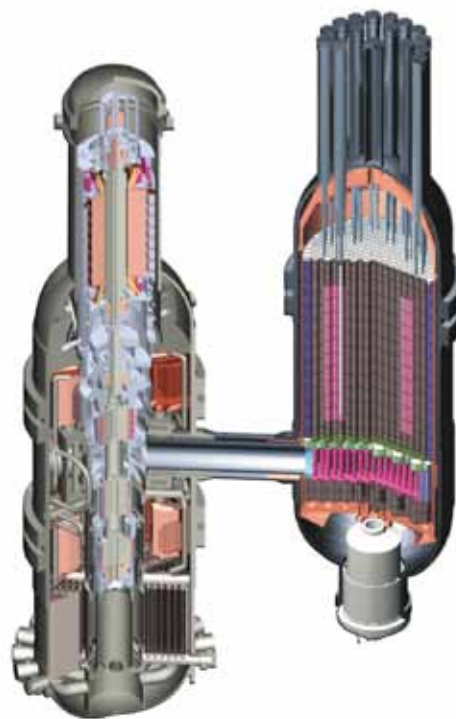
11. NEXT STEPS IN U.S.-RUSSIAN NUCLEAR COOPERATION

As the countries that possess more than 95% of the world's nuclear weapons, most of the world's weapons-usable nuclear material, and the world's longest experience in nuclear energy, the United States and Russia bear special responsibilities for strengthening global efforts to minimize the risks and maximize the benefits of the use of nuclear energy. Expanded U.S.-Russian cooperation will be essential in achieving this objective.

Russia and the United States must work together to resolve proliferation issues in Iran and North Korea; strengthen the global nonproliferation regime; reduce the numbers, roles, and readiness of nuclear arms; secure nuclear material across the globe and prevent nuclear terrorism; and promote safe, secure, and peaceful growth of nuclear energy.

Over the past year, Russia and the United States have worked to “reset” their relationship. In the nuclear field, they have negotiated the New START treaty;⁶⁰ endorsed the common vision of a world free of nuclear weapons; worked together to prepare for the nuclear security summit and strengthen the Global Initiative to Combat Nuclear Terrorism; continued their cooperation to secure and consolidate nuclear weapons and weapons-usable nuclear materials; jointly helped pass UN Security Council 1887, supporting a broad range of steps to strengthen the nonproliferation regime; worked together to gain support on the Board of Governors for an expanded budget for the IAEA; jointly supported Board of Governors approval for a far-reaching IAEA agreement on Russia's International Uranium Enrichment Center at Angarsk; worked with other countries around the world to achieve a consensus in supporting action on nonproliferation, disarmament, and civil use of nuclear energy at the 2010 NPT Review Conference; and established a high-level joint working group on nuclear energy and nuclear security. The United States recast its plans for missile defense in Europe in a way that Russia sees as less threatening to its strategic deterrent.

Differences remain, however, over a range of issues. Negotiation of New START proved to be unexpectedly difficult and contentious, making it clear



Russia has recently launched the *Academician Lomonosov*, carrying the first factory-built floating reactor, intended for use in Russia's far North. Future factory-built reactors, such as the high-temperature gas reactor pictured here, being developed in an international project led by Russia and the United States, could have high levels of safety, security, and proliferation-resistance built-in, and might be deployed around the world.

Source: General Atomics

⁶⁰ Presidents Medvedev and Obama signed New START on April 8. The treaty text can be found at <http://www.state.gov/documents/organization/140035.pdf> (accessed 8 June 2010) and the protocol text can be found at <http://www.state.gov/documents/organization/140047.pdf> (accessed 8 June 2010).

that there are difficult discussions ahead on a subsequent agreement. The two countries have both points in common and major disagreements in their approaches to the crisis over Iran's nuclear program. While cooperation on securing nuclear stockpiles continues, hopes for a new presidential-level initiative in that area have not come to fruition and a new agreement on consolidating nuclear materials has not been completed. No progress has been made on the question of whether both sides should declare more of their HEU and plutonium to be excess to their military needs and available for disposition, or on establishing international monitoring of excess plutonium stockpiles. Disagreements remain on missile defense. While both Russia and the United States support entry into force of the Comprehensive Test Ban Treaty (CTBT) and negotiation of a fissile cutoff, there has been little progress in either area. The 123 agreement has not come into force, slowing a broad range of civilian nuclear energy cooperation.

It is time for Russia and the United States to take the next steps in resetting their nuclear relationship. With respect to nuclear energy, Russia and the United States should:

- Bring the 123 agreement into force;
- As described in previous chapters, work together, and with other countries, to address safety, security, and nonproliferation issues related to nuclear energy in the United States, Russia, and worldwide;
- Work together to limit the spread of enrichment and reprocessing facilities, and to move toward increasing emphasis on multinational or international control of nuclear fuel cycle facilities around the world;
- Transform the joint action plan for nuclear energy cooperation into a specific set of steps to be implemented in the near term;
- Establish a multinational joint venture for factory-built reactors and “cradle-to-grave” nuclear services, as described in this report;
- Expand joint nuclear R&D, focused on the most critical issues for the future of nuclear energy; and
- Expand cooperation to include other key nuclear energy states.
- With respect to steps beyond nuclear energy development that will help build the foundation for large-scale nuclear energy growth, the United States and Russia should:
 - Ratify the New START treaty and the CTBT;
 - Begin discussion on further nuclear arms reductions;
 - Launch a new presidential-level initiative to consolidate and secure nuclear stockpiles and ensure that effective security measures and strong security cultures are sustained over time, as part of working together to achieve the shared goal of effective security for all nuclear stockpiles worldwide within four years;
 - Engage with current and future “hard cases” for nonproliferation, including Iran and North Korea, working with other countries to develop comprehensive packages of incentives and disincentives that are large enough and credible enough to convince these countries that it is in their interests to accept verifiable constraints on their nuclear programs;

- Work to begin negotiation of a fissile cutoff;
- Build on UNSCR 1887, UNSCR 1540, and the consensus results of the May 2010 NPT review, in order to gain support for measures to strengthen the global nonproliferation regime, including stronger inspections, better enforcement, strengthened constraints on enrichment and reprocessing technologies, and steps to reduce the demand for nuclear weapons around the world.

This is a broad and crucial agenda. Success in pursuing it would serve vital Russian and U.S. national interests, contributing to better prospects for peace and prosperity around the world. Success can only be achieved by Russia, the United States, and other countries working together. The time to begin is now.

Belfer Center for Science and International Affairs

Harvard Kennedy School

79 JFK Street

Cambridge, MA 02138

Fax: (617) 495-8963

Email: belfer_center@harvard.edu

Website: <http://belfercenter.org>

Russian Research Center “Kurchatov Institute”

1, Academician Kurchatov Sq.

123182 Moscow, Russia

Fax: +7 499 196 18 70

E-mail: mvk@kiae.ru

Website: www.kiae.ru

Copyright 2010 President and Fellows of Harvard College